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# PRECAST/PRESTRESSED CONCRETE EXPERIMENTS PERFORMANCE ON NON-LOAD BEARING SANDWICH WALL PANELS

Clay J. Naito
Department of Civil and Environmental Engineering
Lehigh University
117 ATLSS Drive
Bethlehem, PA 18015

John M. Hoemann
U.S. Army Engineer Research & Development Center
3909 Halls Ferry Road
CEERD-GS-M
Vicksburg, MS 39180-6199

Jonathon S. Shull
Black & Veatch, Federal Services Division
1805 Meadow Moor Drive
Webb City, MO 64870

Aaron Saucier and Hani A. Salim
Department of Civil and Environmental Engineering
University of Missouri
E2509 Lafferre Hall
Columbia, MO 65211-2200

Bryan T. Bewick and Michael I. Hammons
Airbase Technologies Division
Air Force Research Laboratory
139 Barnes Drive, Suite 2
Tyndall Air Force Base, FL 32403-5323

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BRYAN T. BEWICK
Work Unit Manager

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DEBRA L. RICHLIN
Chief, Airbase Engineering Development Section

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ALBERT N. RHODES, PhD
Chief, Airbase Technologies Division

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# Naito, Clay J.; ## Hoemann, John M.; ** Shull, Jonathon S.; ### Saucier, Aaron; ### Salim, Hani A.; * Bewick, Bryan T.; * Hammons, Michael I.

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*Air Force Research Laboratory
Materials and Manufacturing Directorate
Airbase Technologies Division
139 Barnes Drive, Suite 2
Tyndall Air Force Base, FL 32403-5323

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# 1. INTRODUCTION

To comply with the energy efficiency and build green initiatives contained in the Energy Policy Act of 2005 and Energy Independence Security Act of 2007, the Anti-Terrorism and Force Protection (ATFP) requirements for building construction, and the "build it faster and more economical" requirements of the Military Construction Transformation initiative, a research program has been conducted by the Air Force Research Laboratory (AFRL) and the Portland Cement Association (PCA) on the performance of insulated concrete wall panels. The purpose of the research is to determine if commercially available wall systems with excellent energy savings performance can provide ATFP for military and government facilities.

The use of insulated precast/prestressed (PC/PS) concrete and insulated tilt-up concrete sandwich panels for exterior walls is common practice in the United States. These forms of construction provide a thermally efficient and high-mass wall that enhances the energy efficiency and blast resistance of the building making it ideal for military and government facilities. In most cases these building systems must be designed against a potential explosive demand. Current design recommendations are very restrictive when using these forms of construction, due in large part to the lack of experimental research data. To address this issue a research program has been conducted to assess the performance of conventional insulated exterior wall systems under blast loading. This report presents the static performance of the wall systems subjected to pseudo-blast pressures. The results indicate that sandwich wall systems provide blast resistance over a large deformation range making these systems useful for ATFP applications. The responses of the panels were found to be sensitive to reinforcement type, shear ties used, and insulation. Detailed discussions of the findings are presented in the conclusions of the report.

The information presented in this report represents the second phase of work under a Cooperative Research and Development Agreement (CRADA) entitled Blast Resistant Concrete Products. The CRADA is between PCA and the Airbase Technology Division of AFRL at Tyndall Air Force Base, Florida. Fabrication, design support, and product donations have also been provided from the Precast/Prestressed Concrete Institute (PCI), the Tilt-Up Concrete Association (TCA), and their member companies. Experiments were conducted and supervised by AFRL staff. National Center for Explosion Resistant Design at the University of Missouri-Columbia performed the static series discussed in this report.


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## 2. OBJECTIVES

The overall research objective is to assess the inherent blast resistance of conventional insulated concrete sandwich wall (CSW) products. The research program is focused on developing models to predict the response of exterior building wall panels to explosive detonations at moderate standoff distances from the structure. In this research program wall systems are examined for each facet of the Portland Cement Association's membership. This includes PC/PS concrete wall panels (PPCWPs) for the PCI, tilt-up concrete wall panels for the TCA, masonry walls for the National Concrete Masonry Association, cast-in-place walls for the National Concrete Ready Mix Association, and insulated concrete wall panels for the Insulated Concrete Form Association.

For all concrete associations the objectives of the research are the same:

- Verify if conventional wall systems are capable of resisting a significant blast event.
- Identify if a wall system is capable of providing enough protection for temporary operation and/or continued function after a blast event.
- Develop predictive models for estimating the response of wall panels subjected to exterior blast generated pressure demands.
- Determine recommendations for acceptable deformation, rotation, and ductility limits for the wall panels examined.

This report examines the research objectives as they apply to PPCWPs. A series of quasi-static uniform loading experiments were conducted on standard PCI and TCA sandwich wall panels. The results of the experiments are used to model the resistance and deformation response of PPCWPs. Forty-six single-span walls and 12 two-span walls were examined. This project report provides details of the static test specimens, test configuration, results and comparative response.

The initial static test series is used to define the resistance and failure mode of standard commercially available designs for PC/PS concrete and tilt-up CSWs. The fundamental test results provide the necessary data to evaluate current static resistance functions and dynamic performance limits for sandwich walls constructed using different types of insulation, wythe connections, levels of composite action, and construction techniques. Ultimately, the results will provide valuable information for PCI/TCA program finite element models and lead to new design documentation and engineering level predictive tools for blast resistant sandwich concrete walls. These results will also be considered in providing guidance for designing government and military structures for ATFP standards using PCI/TCA construction methods.

### 2.1. Wall Performance Criteria

The experimental program results will be compared with current recommendations on wall performance and response. The performance of wall panels under blast demands are based on the level of damage achieved. These levels are associated with either displacement ductility or support rotation. For a uniformly loaded simply supported wall system the displacement ductility, $\mu$, is defined as the displacement at midspan, $\Delta_{mid}$, divided by the yield displacement, $\Delta_{y\text{-}mid}$, of the panel.

$$\mu = \Delta_{mid} / \Delta_{y\text{-}mid} \qquad (1)$$


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The support rotation, θ, for a simply supported system is directly related to $\Delta_{mid}$, using the following formulation

$$\theta = \tan^{-1}[\Delta_{mid}/(L/2)] \quad (2)$$

where $L$ is defined as the span length. It is important to note that the support rotation limits are not placed on the system as a means of checking the rotation capability of the supports. Instead the criterion is used to assess the midspan response relative to the span. Under this method long-span panels have a greater allowable midspan displacement than a short-span panel.

The response of the panel is categorized based on the amount of damage in the system as a result of the blast demand. The allowable damage for a given threat is determined based on the use of the facility and/or the performance levels established by the owner. The building is rated based on the level of protection (LOP) provided. The protection is divided into High, Medium, Low, Very Low, and Below Anti-Terrorism Standards. The LOP are in turn determined based on the damage level of the building components. The component damage levels are determined in accordance with the descriptions in Table 1 as developed by the Protective Design Center (PDC) of the US Army Corp [PDC 2008]. Insulated sandwich wall panels are considered a non-structural component. These panels are non-load bearing and their loss would have little effect on the overall structural stability of the building in the area of loss. Consequently the Building

**Table 1. Damage Level Definitions [PDC 2008]**

| Component Damage Level | Description of Component Damage | Building Level of Protection | Limit for Reinforced Concrete Element in Flexure w/ No Shear Reinforcement and w/o Tension Membrane | Limit for Prestressed Concrete Element in Flexure w/o Tension Membrane and Reinforcement Index, $\omega_p{}^1 < 0.15$ |
|---|---|---|---|---|
| Superficial Damage | Component has no visible permanent damage | High | $\mu \leq 1.0$ | $\mu \leq 1.0$ |
| Moderate Damage | Component has some permanent deflection. It is generally repairable, if necessary, although replacement may be more economical and aesthetic | Medium | $\mu > 1.0$<br>$\theta \leq 2.0^{o}$ | $\mu > 1.0$<br>$\theta \leq 1.0^{o}$ |
| Heavy Damage | Component has not failed, but it has significant permanent deflections causing it to be unrepairable | Low | $2.0^{o} < \theta \leq 5.0^{o}$ | $1.0^{o} < \theta \leq 2.0^{o}$ |
| Hazardous Failure | Component has failed, and debris velocities range from insignificant to very significant | Very Low | $5.0^{o} < \theta \leq 10.0^{o}$ | $2.0^{o} < \theta \leq 3.0^{o}$ |
| Blowout | Component is overwhelmed by the blast load, causing debris with significant velocities | Below Anti Terrorism Standards | $\theta > 10.0^{o}$ | $\theta > 3.0^{o}$ |

[1]Prestressed reinforcement index, $\omega_p = A_{ps}/bd_p(f_{ps}/f'_c)$


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LOP and the Component Damage Levels are related as presented in Table 1.

The response limits for various levels of damage of PS and reinforced concrete (RC) flexural components are presented in Table 1. PS concrete components are considered to have limited ductility and, therefore, have lower response limits than non-PS or RC elements. For example a RC panel is considered to be at a Blowout Level at a rotation greater than 10º while a PS panel is at the same damage level at a rotation of 3º. The damage level descriptions and the response limits for each level are assessed as part of this research.


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## 3. INSULATED SANDWICH WALLS

CSW panels are widely used across the United States for construction of building systems. These panels consist of an interior concrete section or "wythe," a foam insulating layer, and an exterior concrete wythe as illustrated in Figure 1. The interior and exterior layers are connected to each other using shear ties. Varying the amount and type of shear ties allows the interior and exterior wythe to act at various levels of composite action.

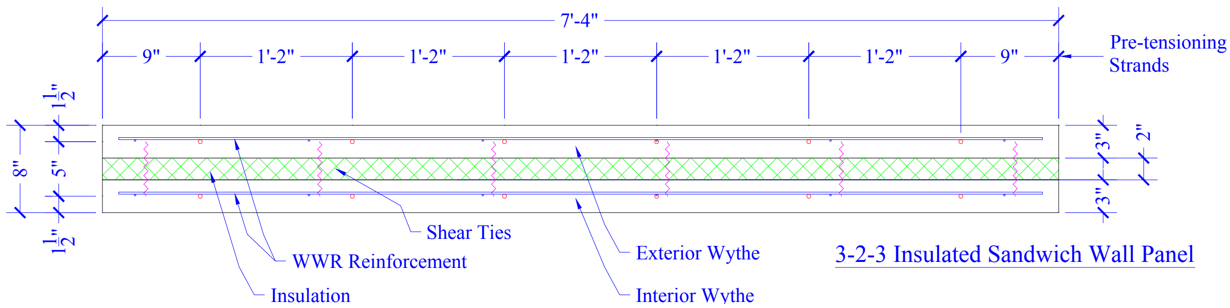


**Figure 1. Sandwich Panel Cross-Section**

Sandwich panels are produced using one of two methods. The first method is referred to as tilt-up construction method; the second is referred to as the PC/PS construction method. The tilt-up method consists of fabricating the panels on the construction site building floor slab or on a temporary casting slab adjacent to the building footprint. For this method steel reinforcement is tied and concrete is placed in the field in a horizontal position (Figure 2). When the panels reach an adequate strength, they are tilted upward into their final position and braced until the floor slabs are installed. This method of construction is used by the TCA. The second method, preferred by members of the PCI, involves prefabricating the wall panels off-site at a casting facility (Figure 3). The facilities are often environmentally controlled and have high quality control allowing for production of panels in all weather conditions. The fabrication at an off-site casting facility also allows the option of having the reinforcing steel to be pre-tensioned prior to placement of the concrete. This allows the panels to be prestressed in compression thus limiting the potential for cracking in transport or during the service life on the building. Both construction methods provide a building envelope that is energy efficient and quick to construct.

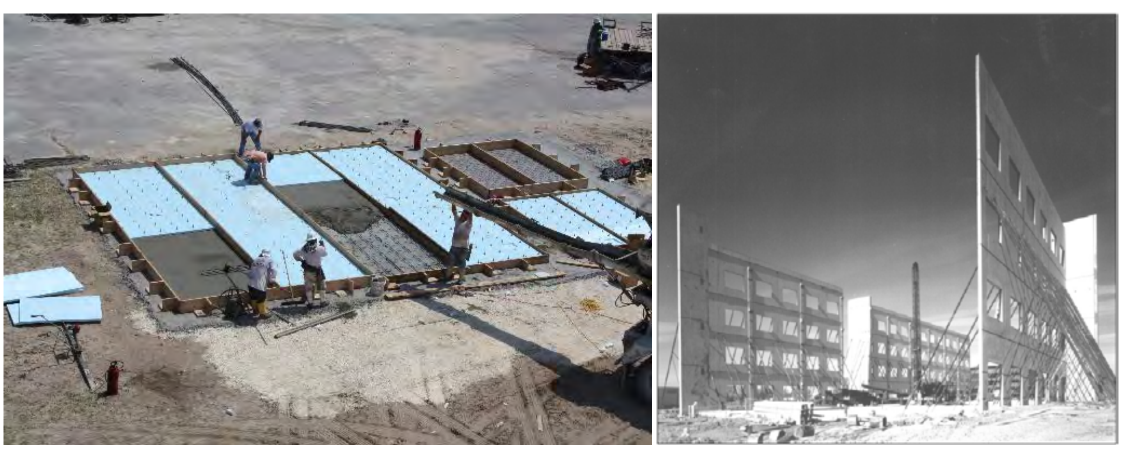

**Figure 2. Tilt-up Concrete Sandwich Wall Construction [TCA 2006]**



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**Figure 3. Prestressed Concrete Sandwich Wall Construction [PCI 1997]**

PC wall panels are typically designed for wind loads and handling loads on the construction site. In most cases the design goal is to preclude cracking. As a consequence, sandwich panels are in most cases designed to be elastic under service loading.

CSWs provide an ideal option for US Government and military facility construction. The foam sandwich provides high levels of insulation resulting in an energy efficient building envelope. The panels can be detailed to achieve any thermal resistance R-value needed. The panels are prefabricated, allowing for rapid erection of the building and short construction schedules. The use of concrete provides a high inertial mass that enhances the blast resistance of the facility against external detonations. This last characteristic is essential for meeting the blast resistance requirements for federal and military facilities. Furthermore, while the thermal properties and construction quality has been well documented, minimal information has been generated on the performance of panels under blast demands. To quantify the blast resistance of these systems a comprehensive experimental program is conducted on insulated sandwich wall panel systems.

## 3.1. Sandwich Wall Configurations

Sandwich walls are available in a variety of forms. The TCA configurations typically consist of a 2.0-to-3.0-in exterior wythe, a 2.0-to-3.0-in foam layer, and a 6-in interior structural wythe. Since this type of construction is only tilted, and rarely transported on site, the walls are most often designed to be non-composite with minimal amount of shear ties used. Fully composite options are also available in TCA configurations. The interior wythe is designed to resist the prevailing wind demand requirements. A typical TCA wall section is illustrated in Figure 4b. PCI type walls come in a larger variety of configurations. They can consist of thin (3-in thick) interior and exterior wythes and a 2-in to 5-in thick foam insulating layer (Figure 4a) or a design utilizing hollow core (Figure 4c), double tees (Figure 4d), or other panels.


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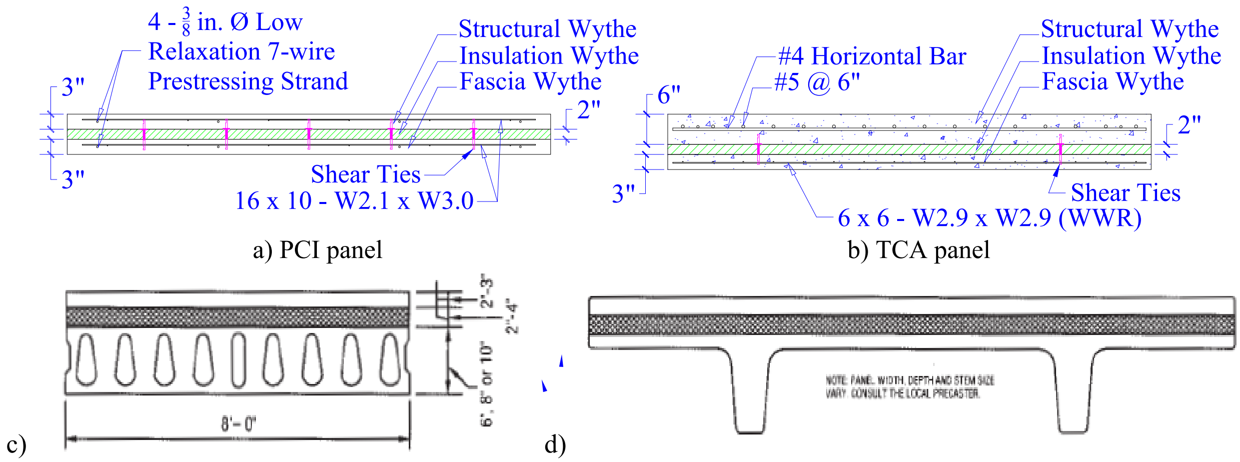


**Figure 4. TCA and PCI Wall Sections (c and d [PCI 1997])**

## 3.2. Insulation Foam Properties

Three standard types of insulation are commonly used in PC sandwich walls. They include expanded polystyrene (EPS), extruded expanded polystyrene (XPS [or XEPS]), and polyisocyanurate (PIMA). EPS is also known as bead board and is often used for low-cost coolers. XPS insulation is commonly produced by Dow or Owens Corning and is sold as Blue Board or Pink Board, respectively. Typical properties of these panel types are summarized in

Table 2. In general the cost, density, thermal resistance, and strength increase from EPS to XPS to PIMA. The insulation used in the research program met the requirements of American Society for Testing and Materials (ASTM) C578 Standard Specification for Rigid, Cellular Polystyrene Thermal Insulation [ASTM 2009a].

**Table 2. Insulation Properties [PCI 1997]**

| Physical Property | Polystyrene | | | | | | Polyisocyanurate | |
|---|---|---|---|---|---|---|---|---|
| | Expanded | | | Extruded | | | Unfaced | Faced |
| Density (lb/ft$^3$) | 0.7–0.9 | 1.1–1.4 | 1.8 | 1.3–1.6 | 1.8–2.2 | 3.0 | 2.0–6.0 | 2.0–6.0 |
| Water absorption (percent volume) | < 4.0 | < 3.0 | < 2.0 | < 0.3 | | | < 3.0 | 1.0–2.0 |
| Compressive strength (psi) | 5–10 | 13–15 | 25 | 15–25 | 40–60 | 100 | 16–50 | 16 |
| Tensile strength (psi) | 18–25 | | | 25 | 50 | 105 | 45–140 | 500 |
| Linear coefficient of expansion (in/in/°F) x 10$^6$ | 25–40 | | | 25–40 | | | 30–60 | |
| Shear strength (psi) | 20–35 | | | -- | 35 | 70 | 20–100 | |
| Flexural strength (psi) | 10–25 | 30–40 | 50 | 40–50 | 60–75 | 100 | 50–210 | 40–50 |
| Thermal conductivity (Btu-in/hr/ft$^2$/°F) | 0.30 | 0.26 | 0.23 | 0.20 | | | 0.18 | 0.10–0.15 |
| Maximum use temperature | 165 °F | | | 165 °F | | | 250 °F | |


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### 3.2.1. Shear Tie Types

Five types of shear ties were examined: C-Grid®, THERMOMASS® composite and non-composite ties, and standard stainless steel C-clips. C-Grid® consists of a carbon fiber mesh placed between the interior and exterior wythe. The proprietary C-Grid® carbon fiber reinforced polymer is produced by Carbon Cast. THERMOMASS® Composite Pins were also examined. These pins consist of glass fiber ties installed between the interior and exterior wythe at a 16-in spacing over the surface of the wall. A standard stainless steel C-clip was also examined to provide a baseline comparison. The ties used in the research program were compared to other connector types available in the US market in Figure 5. Shear Ties Samples: (A) THERMOMASS® non-Composite Tie, (B) THERMOMASS® Composite Tie, (C) Universal Teplo Tie, (D) Dayton Superior Delta Tie, (E) Carbon Cast C-Grid®, (F) Standard Steel C-Clip, and (G) Meadow Burke Steel Welded Wire Girder. The strength and stiffness of these ties and additional tie systems were experimentally determined in an earlier phase of the research and are summarized in AFRL Report AFRL-RX-TY-TR-2009-4600.

Carbon and glass fiber ties were used in the program to represent thermal efficient construction. Steel ties are widely available; however, they create a thermal bridge between the exterior and interior faces of the panel. This results in reduced insulation properties and greater heat transmittance. For example, metal ties spaced at 16 in on center have been shown to increase the heat transmittance of a sandwich wall panel by over 20% [PCI 2004]. This increase can produce cold spots on a wall panel that can produce unsightly condensation. The high thermal transmittance also decreases the insulation capability of the wall which increases heating and cooling costs for the structure. The carbon and glass ties do not produce a significant thermal bridge; however, they are available only as proprietary systems. Consequently, the proprietary systems were used in the research program.

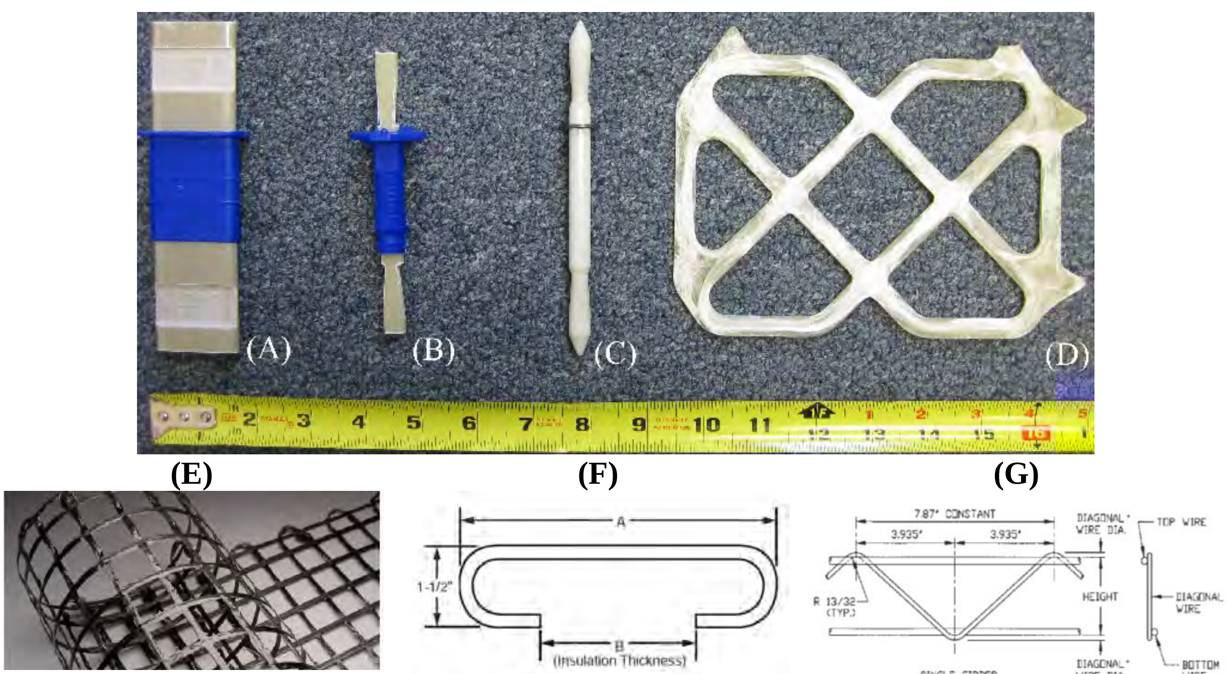


**Figure 5. Shear Ties Samples**


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## 4. DETAILS OF STATIC SPECIMENS

The research program examined the performance of two construction methods. The first method followed the practice of the TCA, the second method followed the practice of the PCI. The panel types were divided into three general configurations: Non-composite non-prestressed walls with an interior structural wythe and a exterior fascia wythe (TCA), partially composite non-prestressed walls (TCA and PCI), and partially composite prestressed walls (PCI). The details are presented with respect to the test type. Three experimental series were conducted:

- Single-span panels with idealized supports
- Multi-span panels with intermediate connections
- Single-span panels with end connections

### 4.1. Single-span Panels with Idealized Supports

A total of 42 single-span specimens with idealized simple supports were examined. Two details typical of tilt-up construction, TS1 and TS2, and 12 details typical of PC/PS concrete construction, PCS1 through PCS9 and PCS3 Type2, were examined. For each detail, three tests were conducted to assess repeatability of the data generated. The three tests for each panel type were designated with A, B and C shear ties. The comprehensive matrix of single-span specimens is summarized in Table 3. Panels were produced by the TCA members and two PCI certified producers, Metromont Corporation and Coreslab Structures. The wythe configuration, insulation material, reinforcement and ties used in each panel are also defined in Table 3.

To develop the experimental subassemblies, PCI and TCA groups were tasked to design wall panels to the following requirements:

- Panel Width = 8 ft
- Panel Length = 24 ft
- Two span with intermediate support at mid-height
- Non-load bearing
- Stripping: Use two-point pick points at one-fifth points from ends and sides of panel
- Erection: Use three-point pick with lower points at 4 ft and 14 ft from lower end of the panel
- Design wind speed 110 mph, exposure C, enclosed building
- Wind Loads computed in accordance with ASCE 7-05
- Panels designed in accordance with American Concrete Institute (ACI) 318-08
- No blast design criteria included
- Occupancy Category IV
- If used, all prestressing shall be 3/8-in diameter grade 270 low relaxation

The wall designs were sectioned to evaluate tributary widths of 16 in for the TCA panels and 32 in for the PCI panels. These thin widths were chosen based on the longitudinal reinforcement and shear ties spacing. In addition, the narrow widths facilitated handling and laboratory testing.


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**Table 3. PCI Static Single-span Specimen Matrix**

| No. | Specimen | Wythe Config. | Insulation | Panel Reinforcement (Longitudinal / Transverse) | Composite Ties | Fabricator |
|---|---|---|---|---|---|---|
| 1–3 | TS1-A,B,C | 6-2-3 | XPS | #3 bar/ WWR | THERMOMASS® - Non-Composite | TCA |
| 4–6 | TS2-A,B,C | 3-2-3 | | #3 bar/ #3 bar | THERMOMASS® - Composite | |
| 7–9 | PCS1-A,B,C | 3-2-3 | EPS | 3/8Ø strand / WWR | Steel C-clip | Metromont |
| 10–12 | PCS2-A,B,C | | | 3/8Ø strand / WWR | C-Grid® | |
| 13–15 | PCS3-A,B,C | | | #5 bar/ WWR | C-Grid® | |
| 16–18 | PCS3 (Type 2)-D, E, F | | | 3/8Ø strand & #5 / WWR | C-Grid® | |
| 19–21 | PCS4-A,B,C | 3-3-3 | XPS | 3/8Ø strand / #3 bar | Steel C-clip | Coreslab |
| 22–24 | PCS5-A,B,C | | | 3/8Ø strand / #3 bar | THERMOMASS® Composite | |
| 25–27 | PCS6-A,B,C | | | 3/8Ø strand / WWR | C-Grid® | Metromont |
| 28–30 | PCS7-A,B,C | | | #5 bar/ #3 bar | THERMOMASS® Composite | Coreslab |
| 31–33 | PCS8-A,B,C | | PIMA | 3/8Ø strand / #3 bar | | |
| 34–36 | PCS9-A,B,C | | | 3/8Ø strand / WWR | C-Grid® | Metromont |
| 37–39 | Tin1A,B,C | 3-4-3 | XPS | 3/8Ø strand / #3 bar (bonded) | Meadow Burke Wire Girder MB-343-7 | Tindall |
| 40–42 | Tin2 A,B,C | | | 3/8Ø strand / #3 bar (unbonded) | Meadow Burke Wire Girder MB-343-7 | |

Two prototype panels were designed by TCA. The details are shown in Figures 6 and 7. The 3-2-3 wall is designed to be partially composite and relies on the use of THERMOMASS® Composite ties. The 6-2-3 wall is designed to be non-composite with the 6-in section acting as the structural wythe and Non-Composite THERMOMASS® ties providing the connection to the fascia wythe.

To preserve symmetry in the static samples, the longitudinal rebar size and spacing was changed from the prototype walls provided by TCA. In addition, due to handling concerns, the cross section width was reduced to 16 in. The specimens were detailed to have one line of THERMOMASS® connectors and two longitudinal reinforcing bars. The spacing and size of the longitudinal reinforcement was chosen to provide the same flexural strength as the prototype panels. Conventional lifting hardware was not used due to the small size of the specimen. Instead reinforcement hooks were included to assist in handling. The schematics of the single-span static specimens are illustrated in Figures 8 and 9.

A similar procedure was conducted for PCI panels. The prototype panels developed by two of the PCI manufacturers, Metromont Corporation and Coreslab Structures, are illustrated in Figures 10 and 11. Metromont designed a 3-2-3 configuration while Coreslab designed a 3-3-3 configuration. The specimens were detailed to have a similar flexural strength per width as the prototype panels. A wide variety of sandwich panel details were developed from the prototypes illustrated in Table 4.


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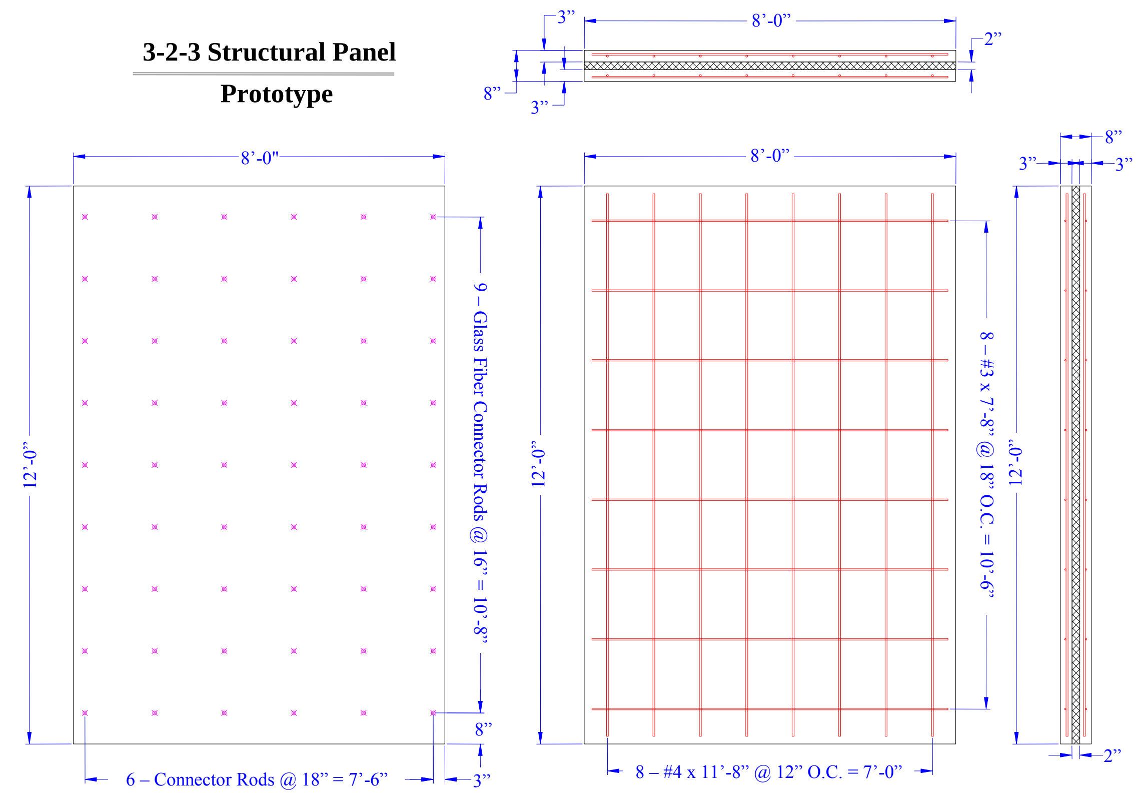


**Figure 6. Prototype TCA 3-2-3 Wall**

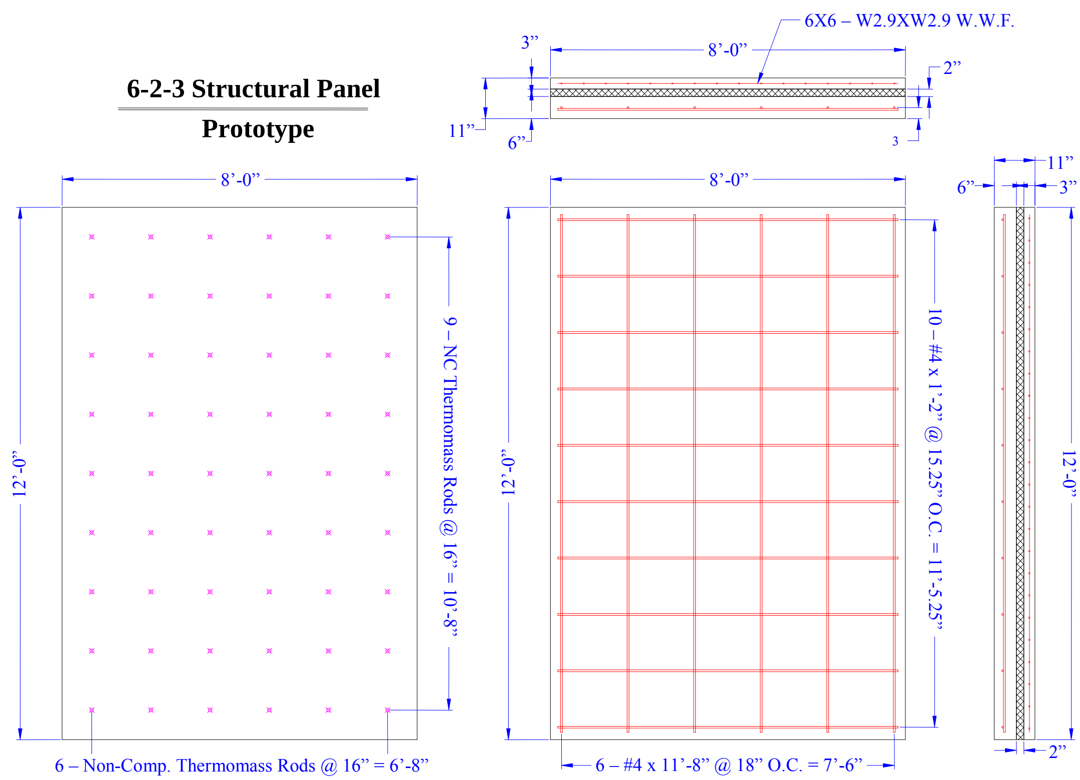


**Figure 7. Prototype TCA 6-2-3 Wall**


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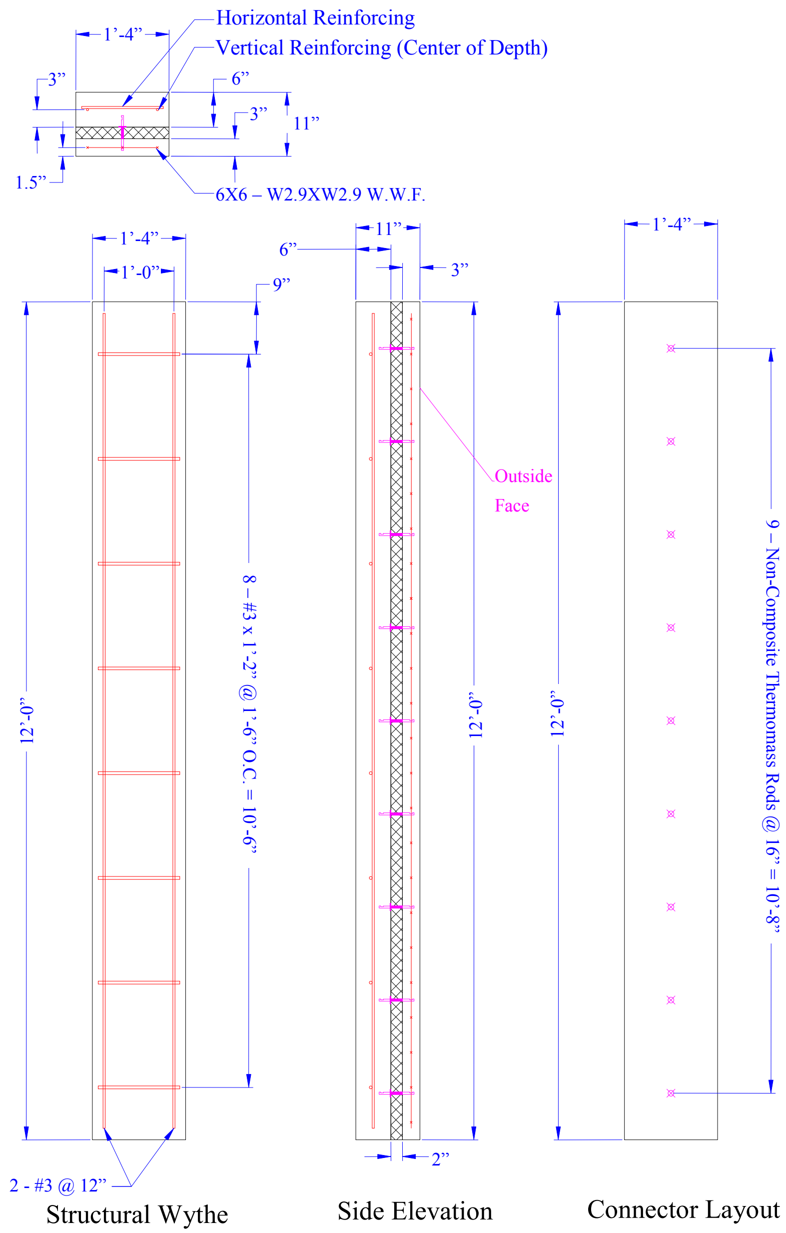


**Figure 8. TCA Non-composite 6-2-3 Single-span Static Specimen TS1 Details**


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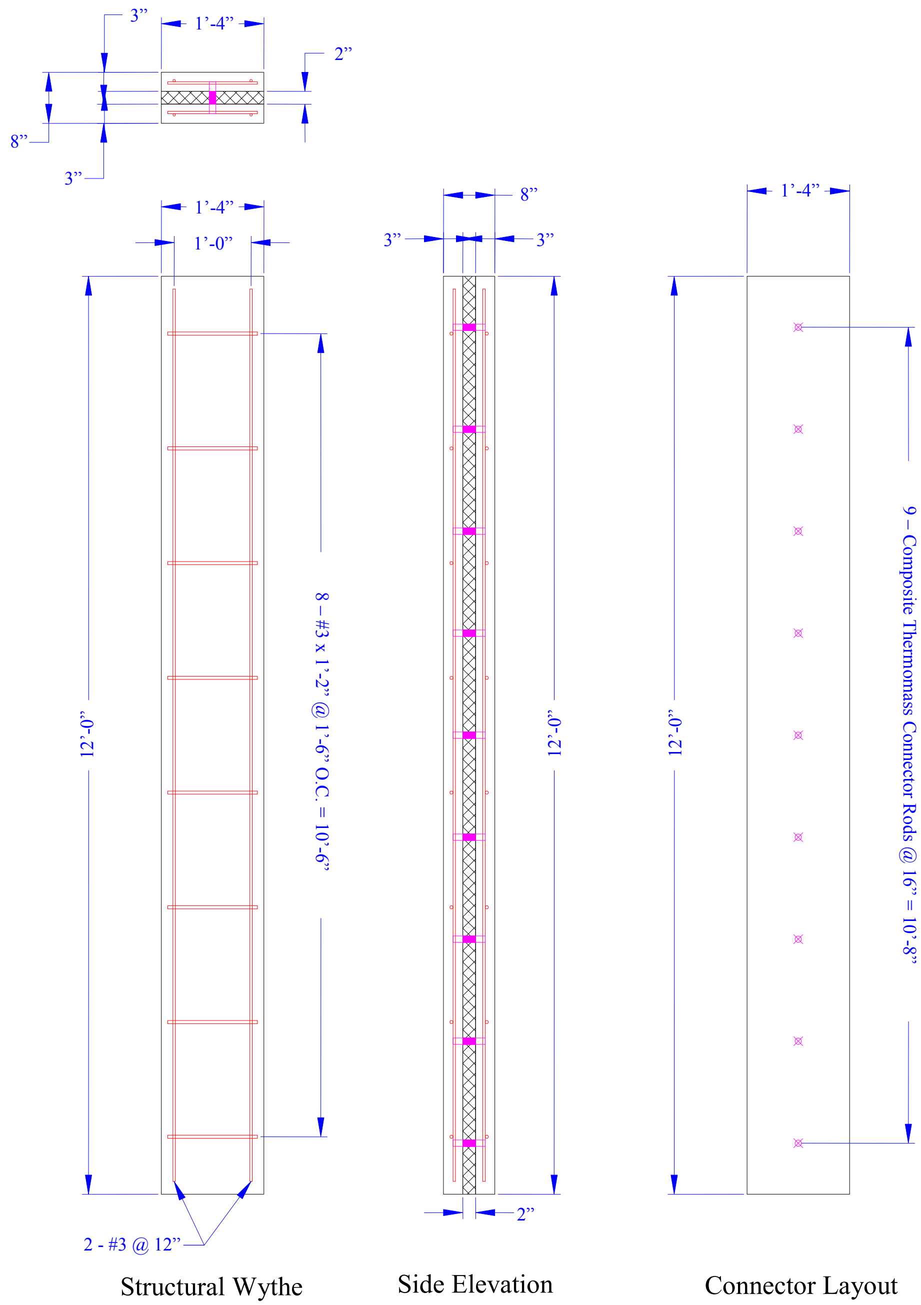


**Figure 9. TCA Composite 3-2-3 Single-span Static Specimen TS2 Details**


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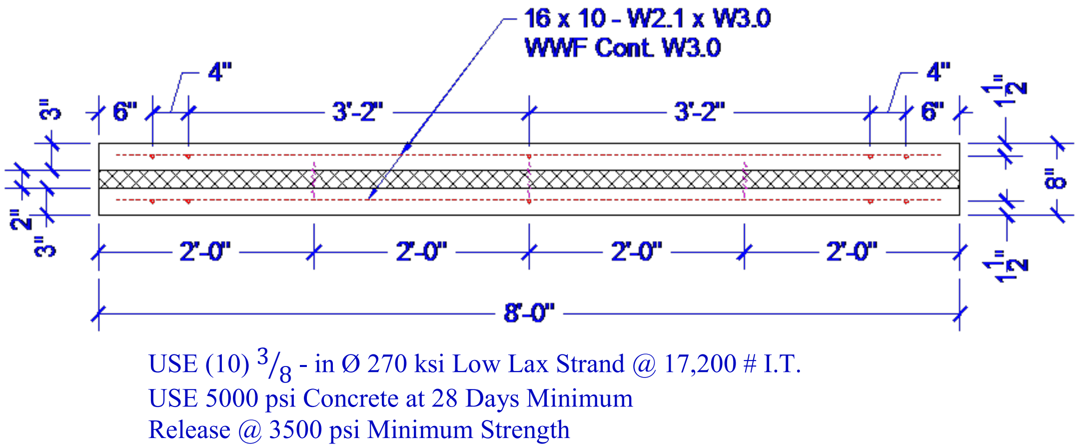



**Figure 10. Metromont PCI Prototype Wall Panel Design**

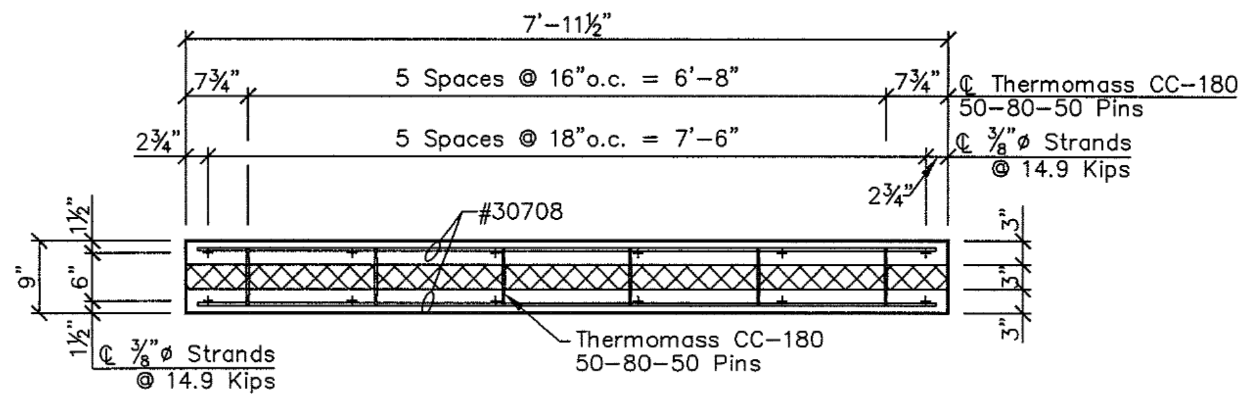
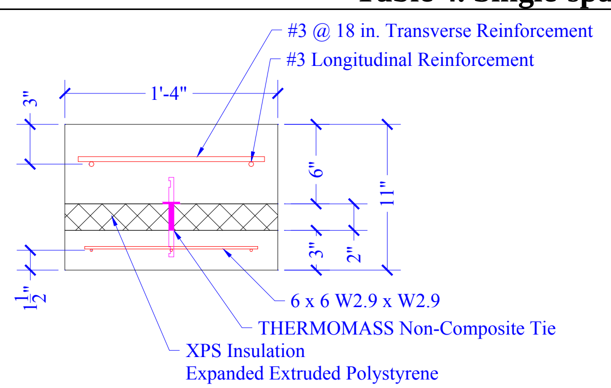


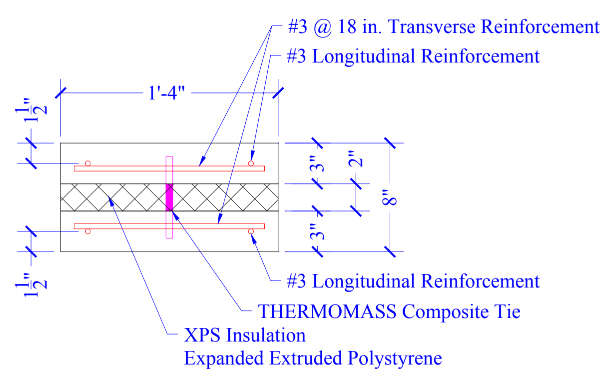

**Figure 11. Coreslab PCI Prototype Wall Panel Design**

The experimental specimen details are summarized in Table 4. The cross-section dimension and the reinforcement and shear tie properties for each panel type are given.

**Table 4. Single-span Specimen Sections**




TS1




TS2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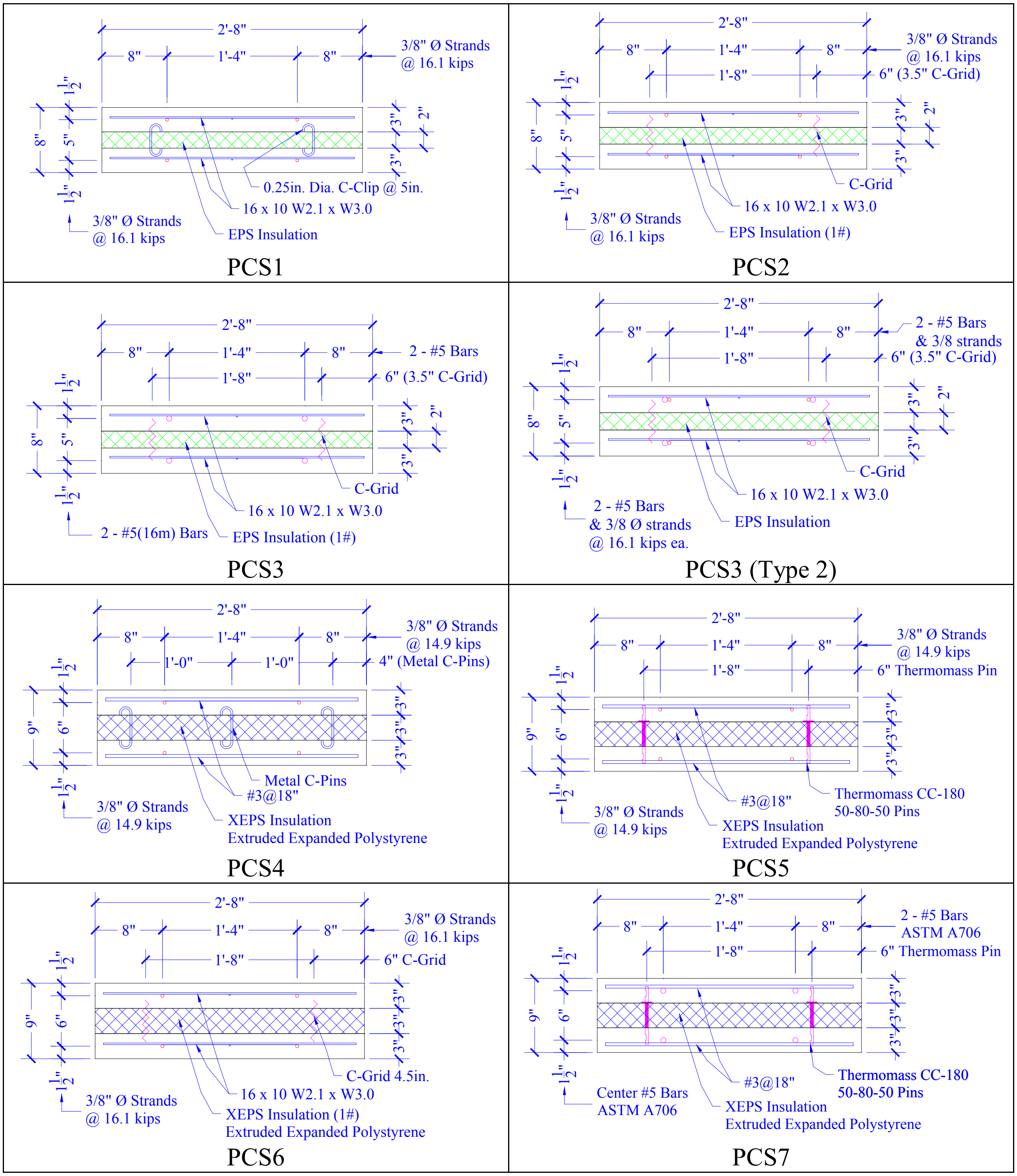




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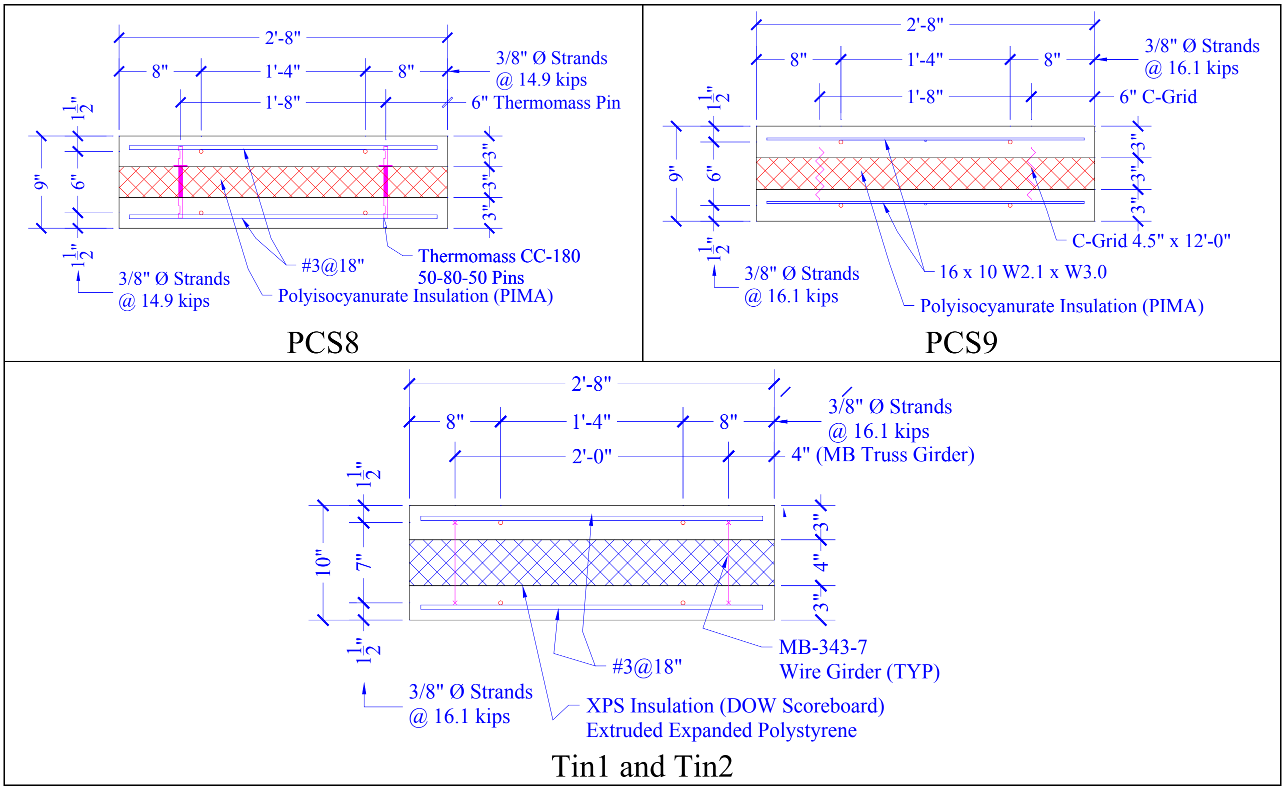


Four combinations of longitudinal and transverse reinforcement were used for the PCI panels. The Metromont panels used welded wire reinforcement (WWR) for transverse reinforcement while the Coreslab and Tindall panels used #3 bars. In addition, two non-PS panels were included: PCS7 and PCS3. For these panels the non-prestressed reinforcement consisting of four #5 bars were used in place of the four 3/8-in diameter prestressing strands. This reinforcement quantity resulted in a comparable ultimate moment capacity between the specimen. The transverse reinforcement layout for the four PCI panel types are illustrated in Figures 12 and 13. Further details of each specimen appear in the results section of the report.

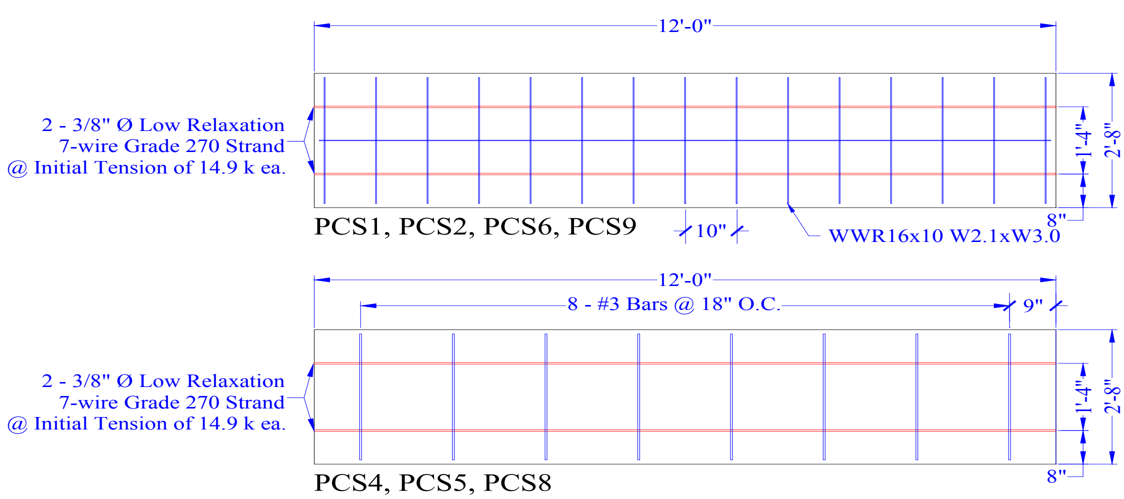


**Figure 12. PCI Panel Reinforcement**


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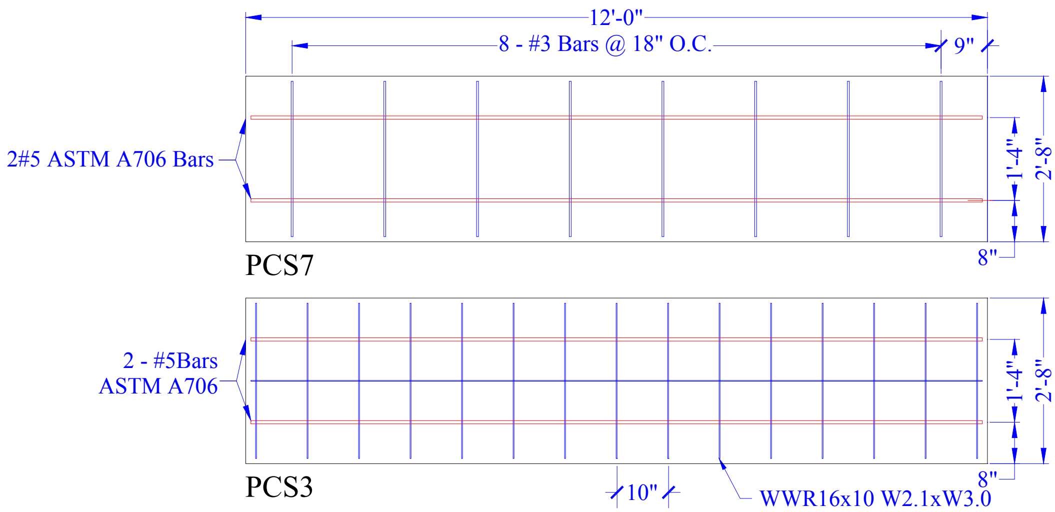


**Figure 13. Control Panel Reinforcement**

Specimens Tindall 1 and Tindall 2 modeled the effectiveness of unbonded reinforcement in enhancing the flexural deformation capacity of sandwich panels. The specimen details are illustrated in Figure 14.

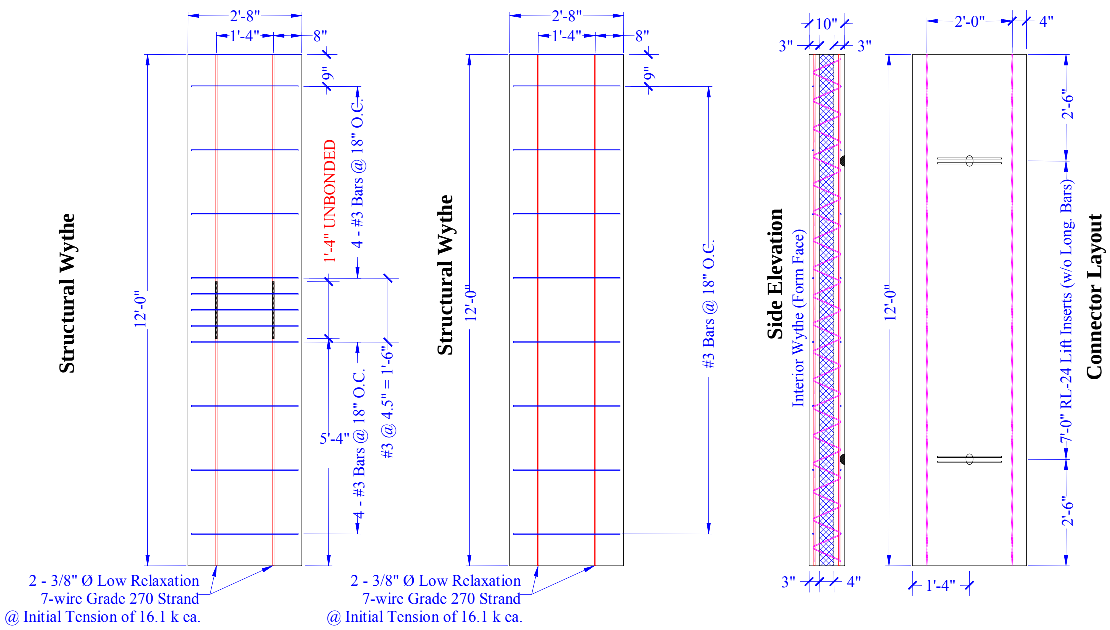


**Figure 14. Tindall Panel Reinforcement**

## 4.2. Multi-span Panels with Intermediate Connections

Five two-span details were examined. These details were chosen to match the standard Tilt-Up Construction and standard Prestressed/Precast Concrete Industry designs. Three TCA type details and two PCI details were examined. Two of each type of TCA detail were tested. These


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specimens are identified as TS3-A and B, TS3-C and D, and TS3-E and F. Three of each type of PCI detail were tested. These specimens are identified as PCD1-A, -B, and -C, and PCD2-A, -B, and -C. The matrix of two-span specimens is summarized in Table 5. Details of each specimen are included in Figures 15-19.

**Table 5. Two-span Specimen Matrix**

<table>
<tr><th>Specimen</th><th>Wythe Config.</th><th>Insulation</th><th>Panel Reinforcement</th><th>Composite Ties</th><th>Connector</th></tr>
<tr><td>PCD1-A</td><td rowspan="3">3-3-3</td><td rowspan="3">XPS</td><td rowspan="3">Prestressed / Rebar</td><td rowspan="3">THERMOMASS® Composite</td><td rowspan="3">Stud Group</td></tr>
<tr><td>PCD1-B</td></tr>
<tr><td>PCD1-C</td></tr>
<tr><td>PCD2-A</td><td rowspan="3">3-2-3</td><td rowspan="3">EPS</td><td rowspan="3">Prestressed / WWR</td><td rowspan="3">C-Grid®</td><td rowspan="3">Stud Group</td></tr>
<tr><td>PCD2-B</td></tr>
<tr><td>PCD2-C</td></tr>
<tr><td>TS3-A</td><td rowspan="6">6-2-3</td><td rowspan="6">XPS</td><td rowspan="6">Reinforced Concrete</td><td rowspan="6">THERMOMASS® – Non-Composite</td><td rowspan="2">Halfen Connector</td></tr>
<tr><td>TS3-B</td></tr>
<tr><td>TS3-C</td><td rowspan="2">No Connector</td></tr>
<tr><td>TS3-D</td></tr>
<tr><td>TS3-E</td><td rowspan="2">Stud Group</td></tr>
<tr><td>TS3-F</td></tr>
</table>

### 4.2.1. Midspan Connection Details

The recommended details for the midspan connection on the two-span panels are described in this section. A standard roller consisting of a pipe bearing on the panel was used for the end connection of each panel. The sliding Halfen connection used in specimen TS3 consisted of a HT5506 connector as illustrated in Figures 20 and 21. This connection is a proprietary system produced by Meadow Burke. Similar connections are available from other vendors such as JVI as illustrated in Figure 22. The JVI connectors were not included in the test series.


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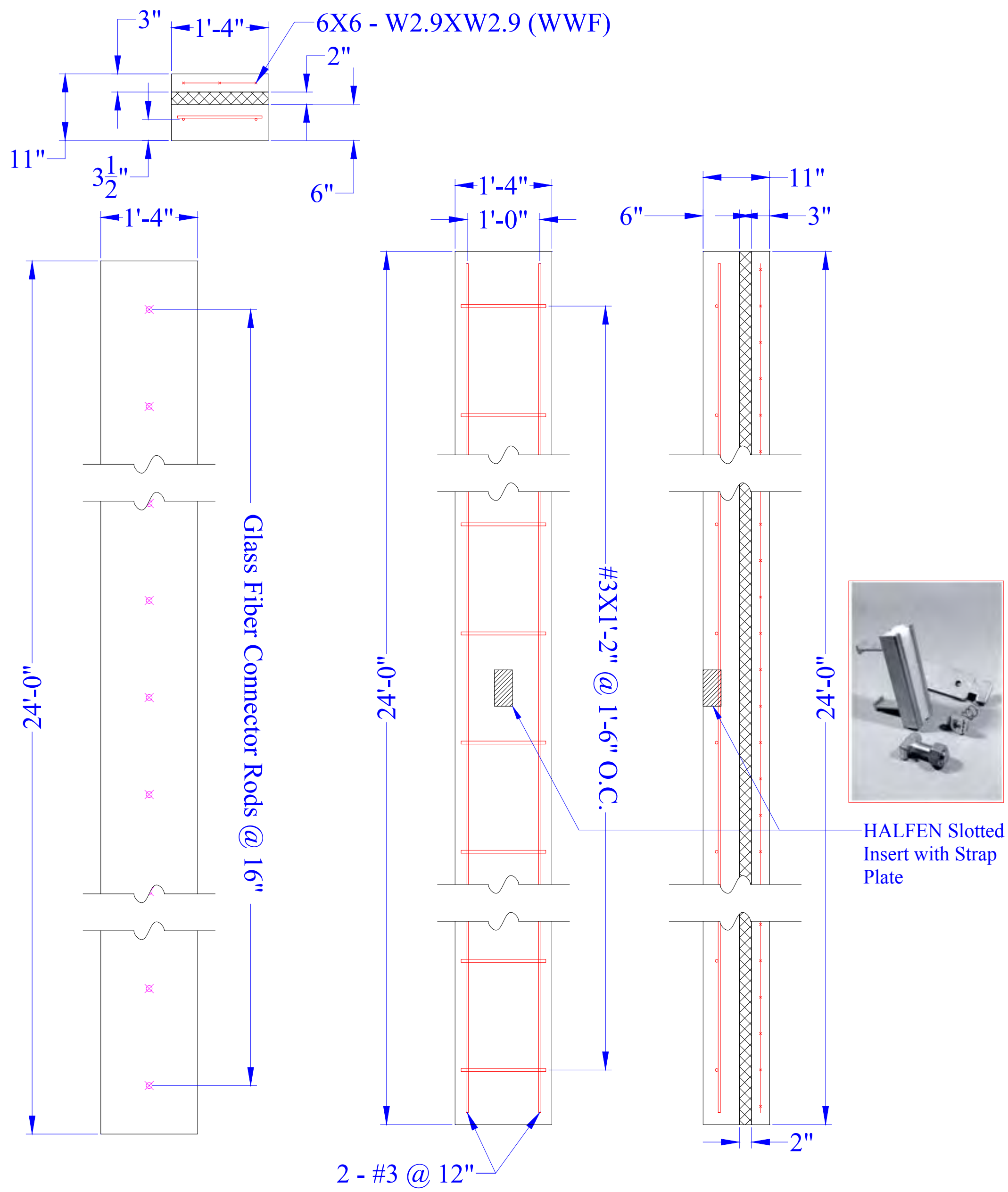


**Figure 15. TCA Two-span Details TS3-A and B**

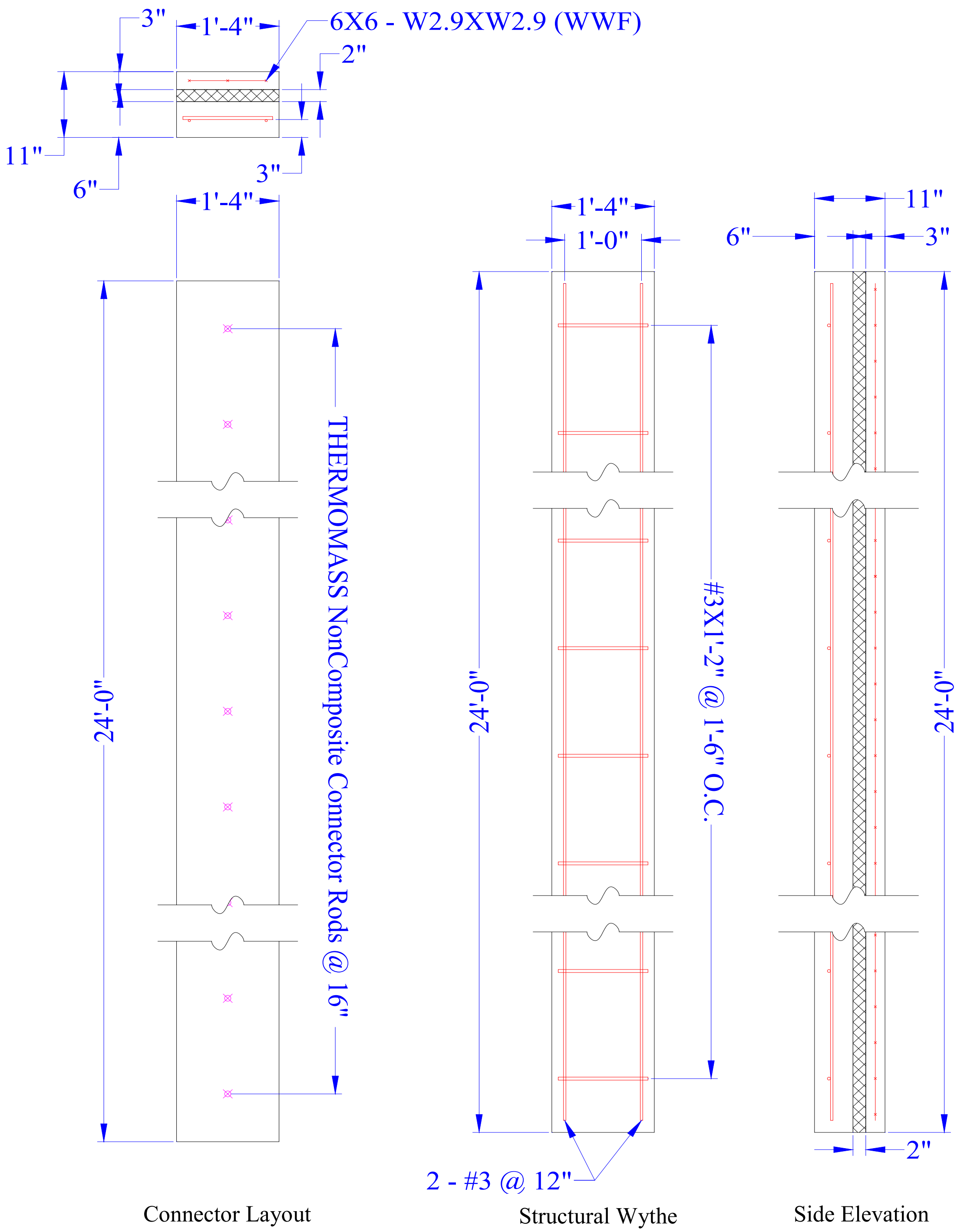


**Figure 16. TCA Two-span Details TS3-C and D**


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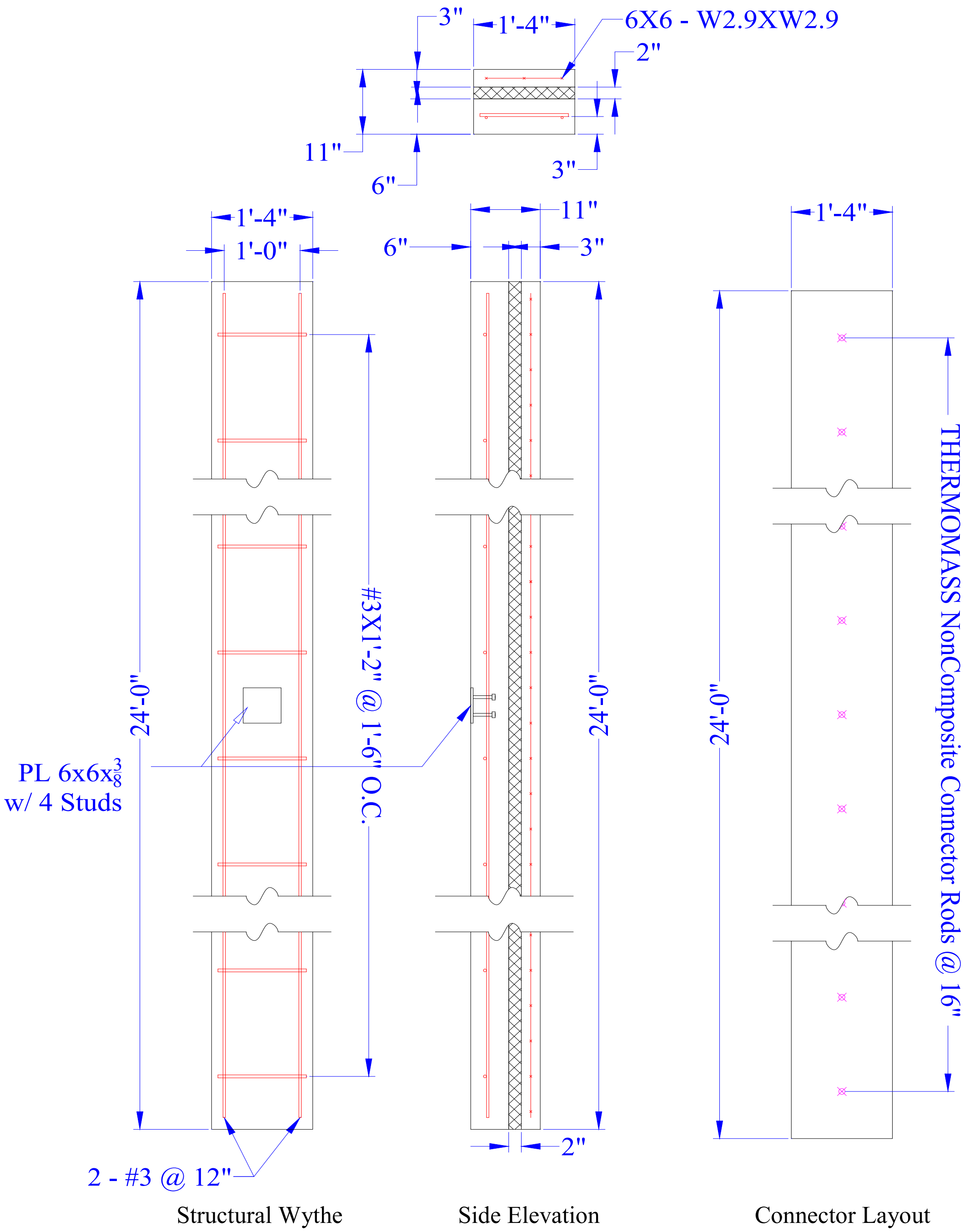


**Figure 17. TCA Two-span Details TS3-E and F**


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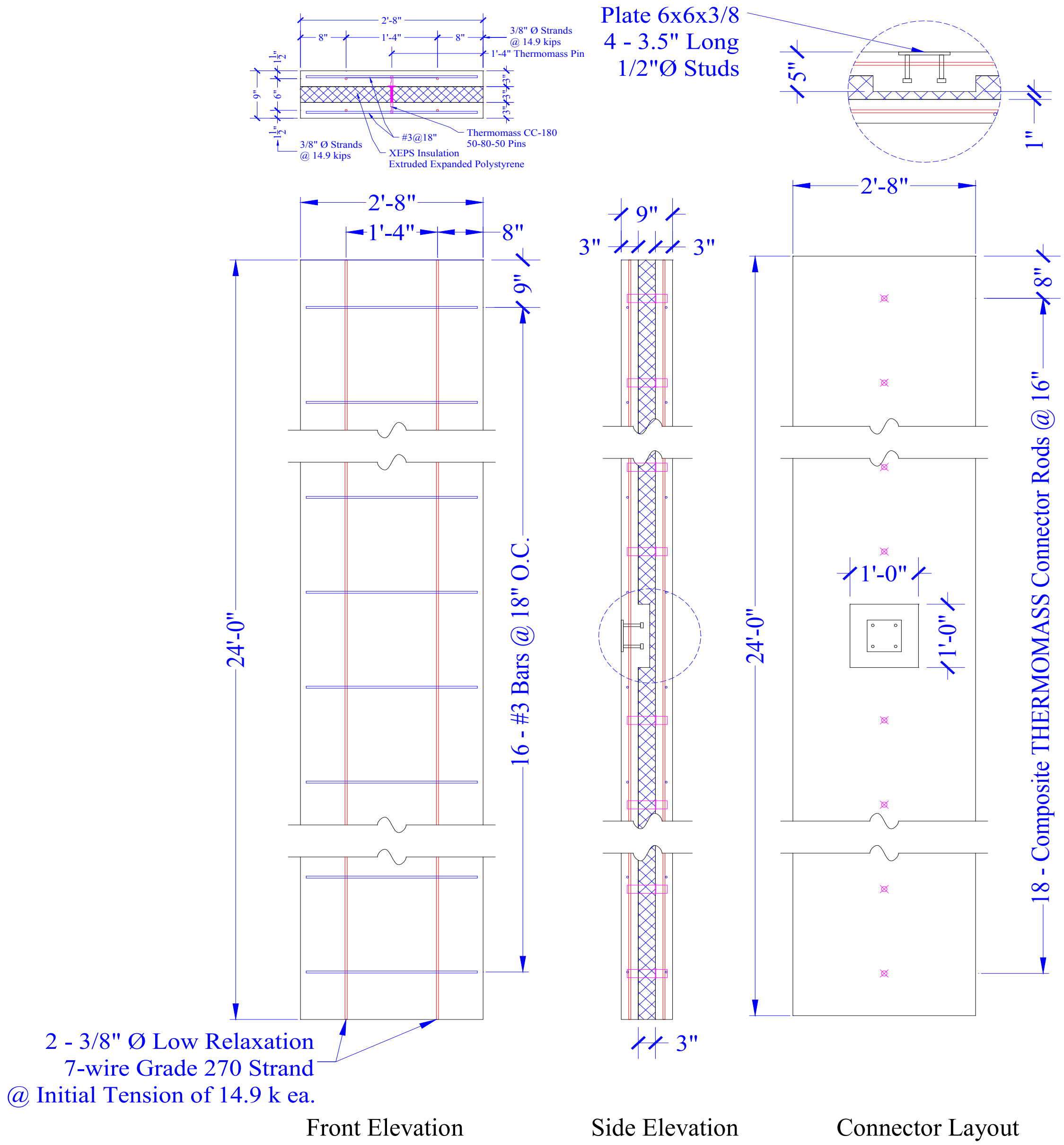


**Figure 18. Coreslab Two-span Panel PCD1**



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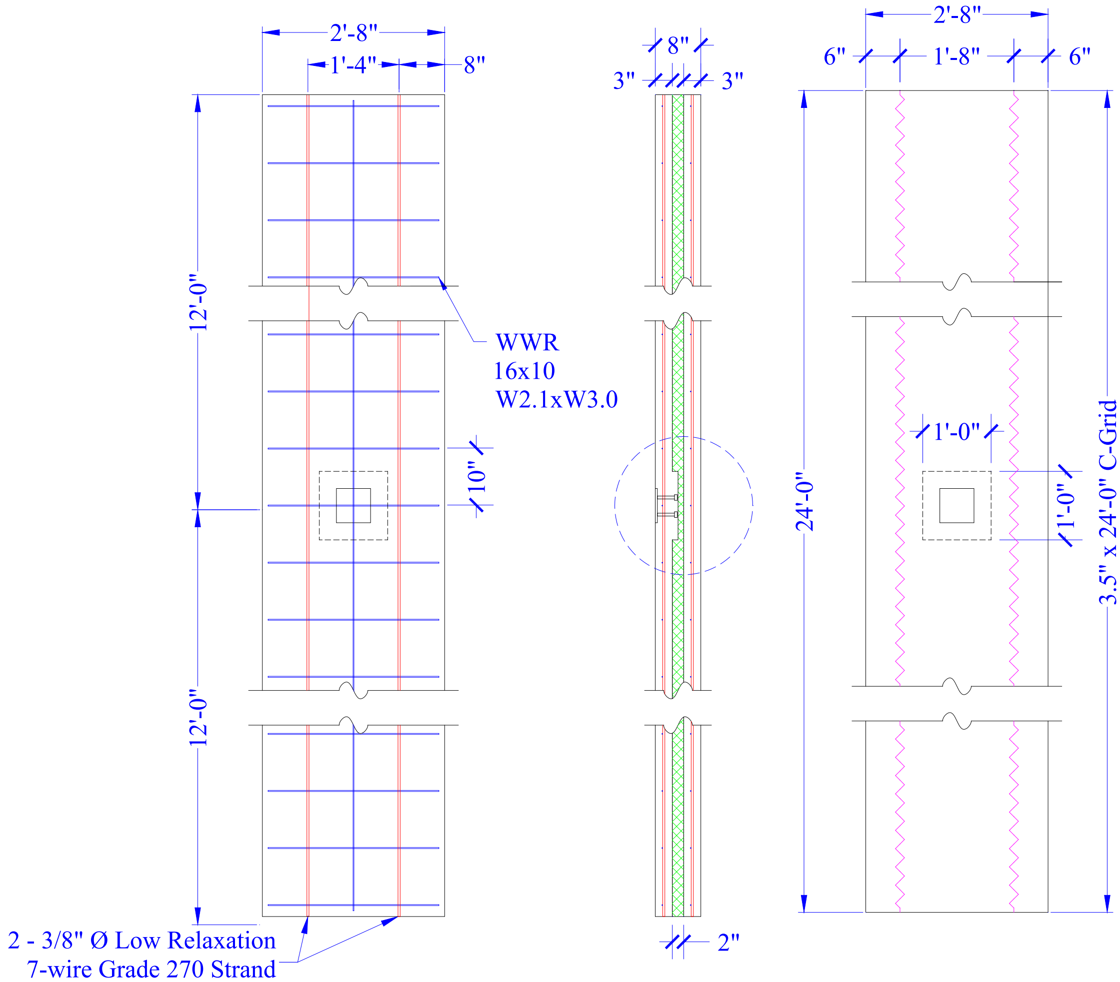
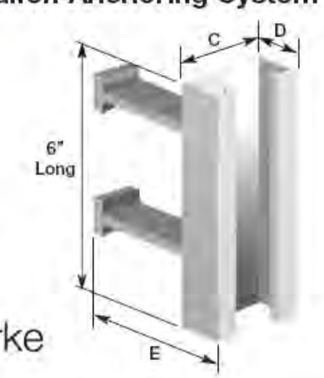


Figure 19. Metromont Two-span Panel PCD2

| ANCHOR CHANNEL SELECTION CHART | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Anchor Channel | HDG Mill Finish | HT3506 HT3506 MF | | HT4506 HT4506 MF | | HT5506 HT5506 MF | | HT6506 TA HT6506 TAMF | |
| Load Direction | | Pull-out | Shear | Pull-out | Shear | Pull-out | Shear | Pull-out | Shear |
| Ultimate Capacity | lb (kN) | 6,650 (29.6) | 7,550 (33.6) | 7,500 (33.4) | 11,300 (50.3) | 11,250 (50.1) | 11,950 (53.2) | 21,200 (94.3) | 20,050 (89.2) |
| Basic Design Load | lb (kN) | 2,200 (9.8) | 2,500 (11.1) | 2,500 (11.1) | 3,750 (16.7) | 3,750 (16.7) | 4,000 (17.8) | 7,050 (31.4) | 6,700 (29.8) |
| Wind Load | lb (kN) | 2,900 (9.8) | 2,500 (11.1) | 3,300 (11.1) | 3,750 (16.7) | 5,000 (22.3) | 4,000 (17.8) | 7,050 (31.4) | 6,700 (29.8) |
| Min. Distances | A In (mm) | 3 (76) | 3-1/2 (90) | 3 (76) | 4 (102) | 4 (102) | 5 (127) | 5 (127) | 8 (203) |
| | B In (mm) | 2 (51) | 2 (51) | 2 (51) | 2 (51) | 3 (76) | 3 (76) | 4 (102) | 4 (102) |
| Dimensions | C In (mm) | 1-1/2 | (38) | 1-9/16 | (40) | 2 | (50) | 2-1/16 | (52) |
| | D In (mm) | 5/8 | (17) | 7/8 | (22) | 1-3/16 | (30) | 1-5/16 | (34) |
| | E In (mm) | 3-1/16 | (77) | 3-1/4 | (82) | 3-1/2 | (90) | 5-1/4 | (134) |

1 Panel Restraint Anchors can be supplied with I-anchor turned 90º to avoid conflict with prestressing tendon, specify "Type L" when ordering.
2 Table is based on 5,000 psi unreinforced, normal weight concrete and a 3:1 safety factor.

Halfen Anchoring System




MeadowBurke

Figure 20. MeadowBurke Halfen Insert Capacity [Meadow Burke 2011]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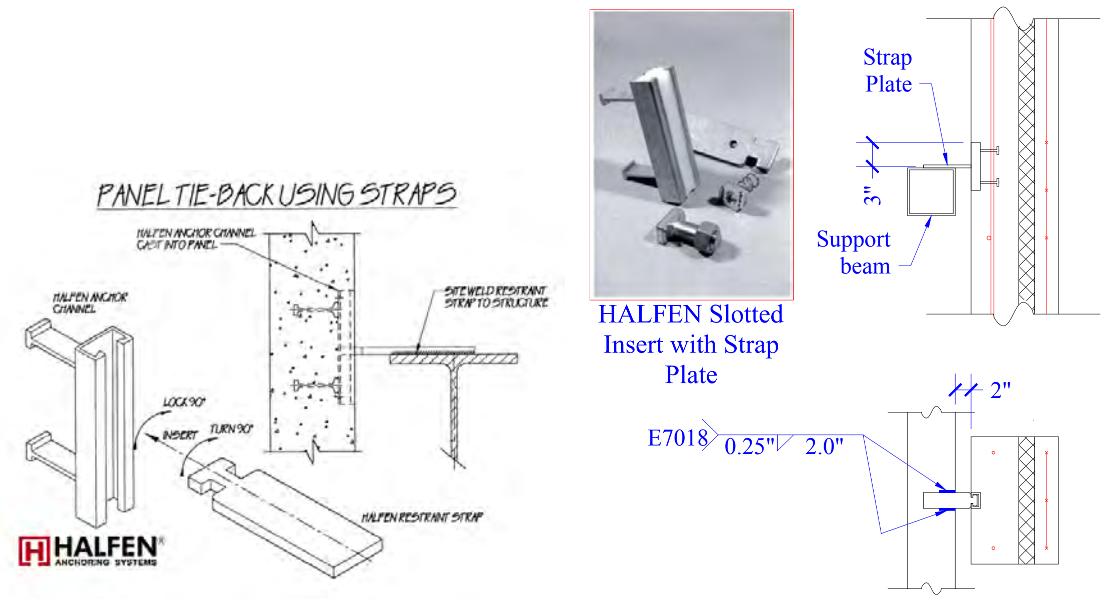


**Figure 21. TS3-A and B Connection Details**

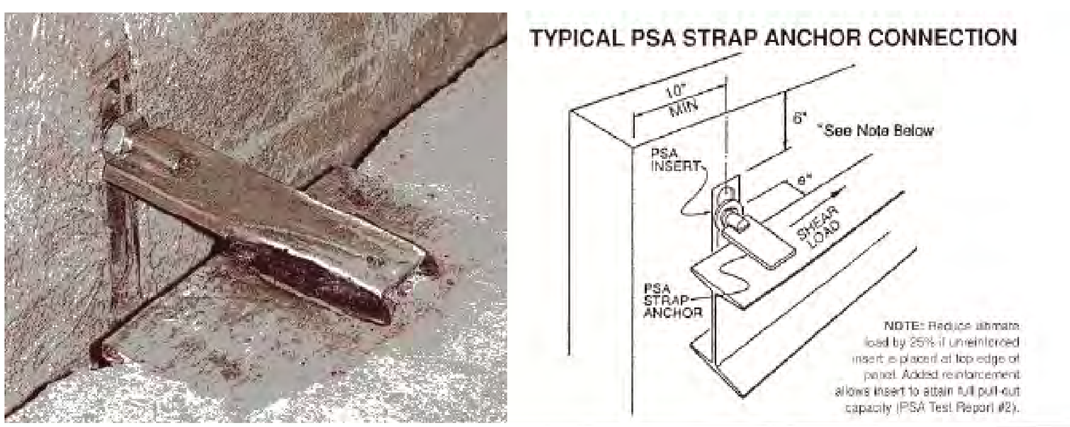


**Figure 22. JVI PSA Insert**

The PCI panels both used standard stud group connections. Two sizes were used as illustrated in Figure 23. Both were placed at midspan of the panel. The variation between specimens is due to the differences in PC producers. Both connections represent a standard embed used by a PCI certified producer. The stud group used on the TCA panels TCA3-E and F consists of a Meadow Burke Rapid-Lok connection. The connection is rated for a 15-kip vertical and 9-kip horizontal service weight load.

The welding details used for the stud group connectors of PCD1, PCD2, and TS3-E and F are illustrated in Figure 24. To provide a baseline comparison panels TS3-C and D were examined without a discrete connector. For these panels the interior wythe bears directly on a roller support.


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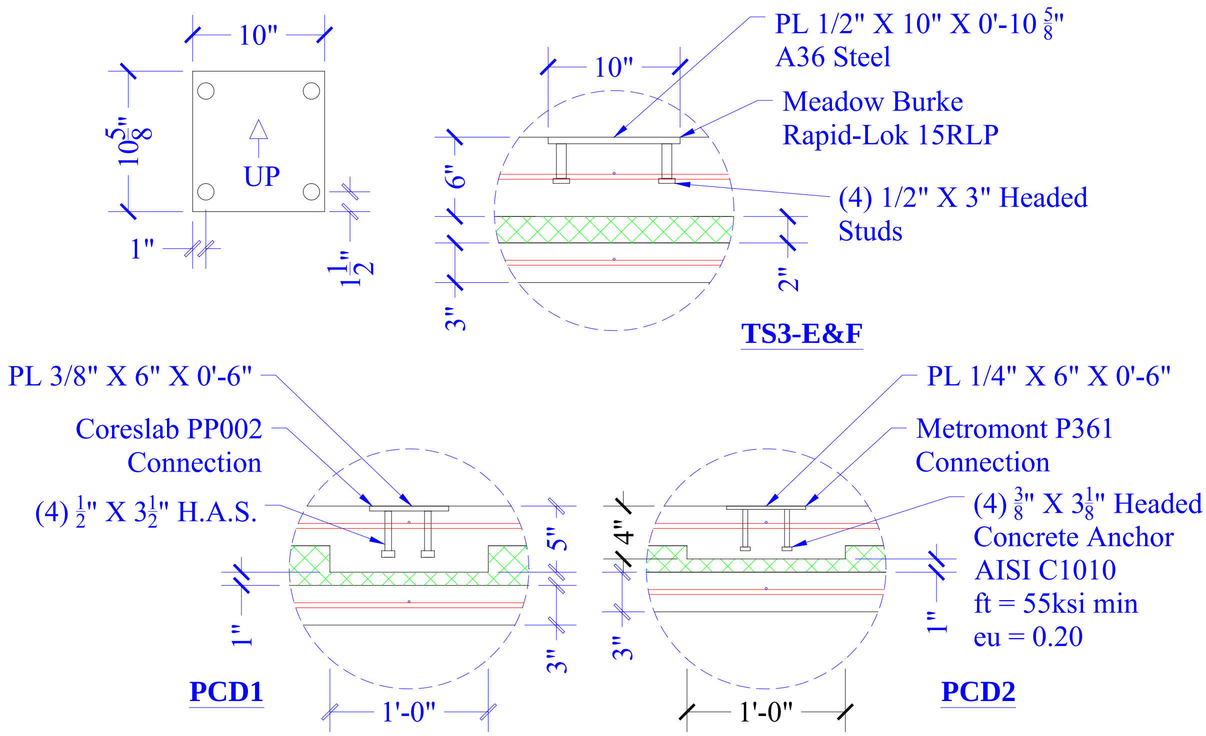


**Figure 23. Connection Details for PCI Panels PCD1 and PCD2**

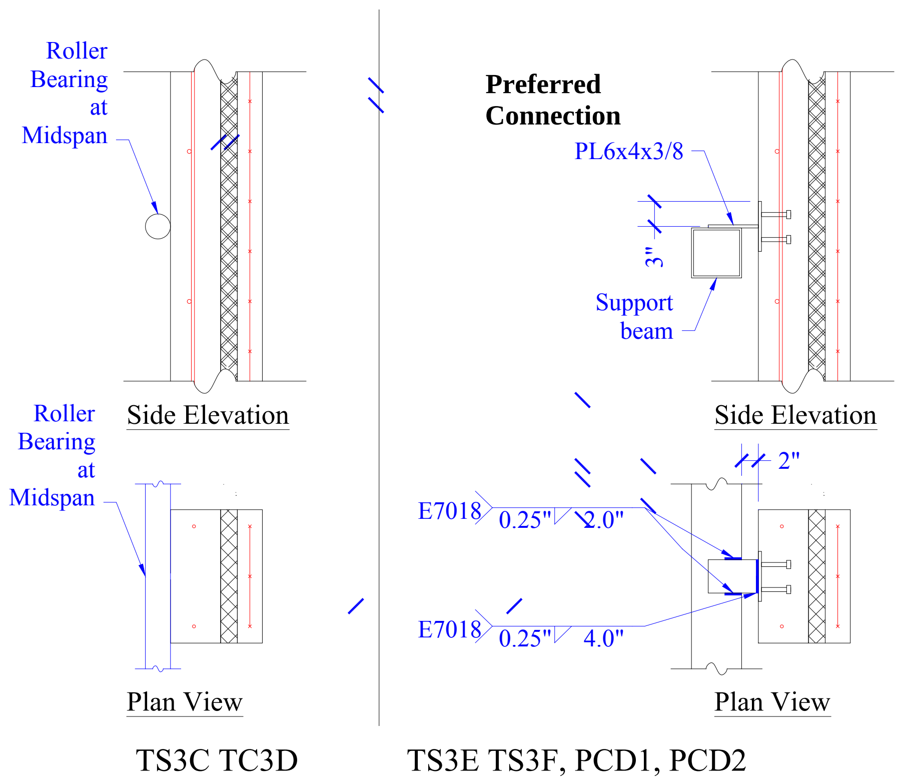


**Figure 24. Connection Details**


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### 4.3. Single-span Panels with End Connections

Four single-span specimens were fabricated and tested to assess the failure modes of standard panel base connections. The panels were fabricated using the same connection at the top and bottom to ensure that the response was symmetric. These specimens are identified as PCS10 and PCS11. The specimen details are illustrated in Figures 25 and 26. The details of the two connections are included in Figures 28 and 29.

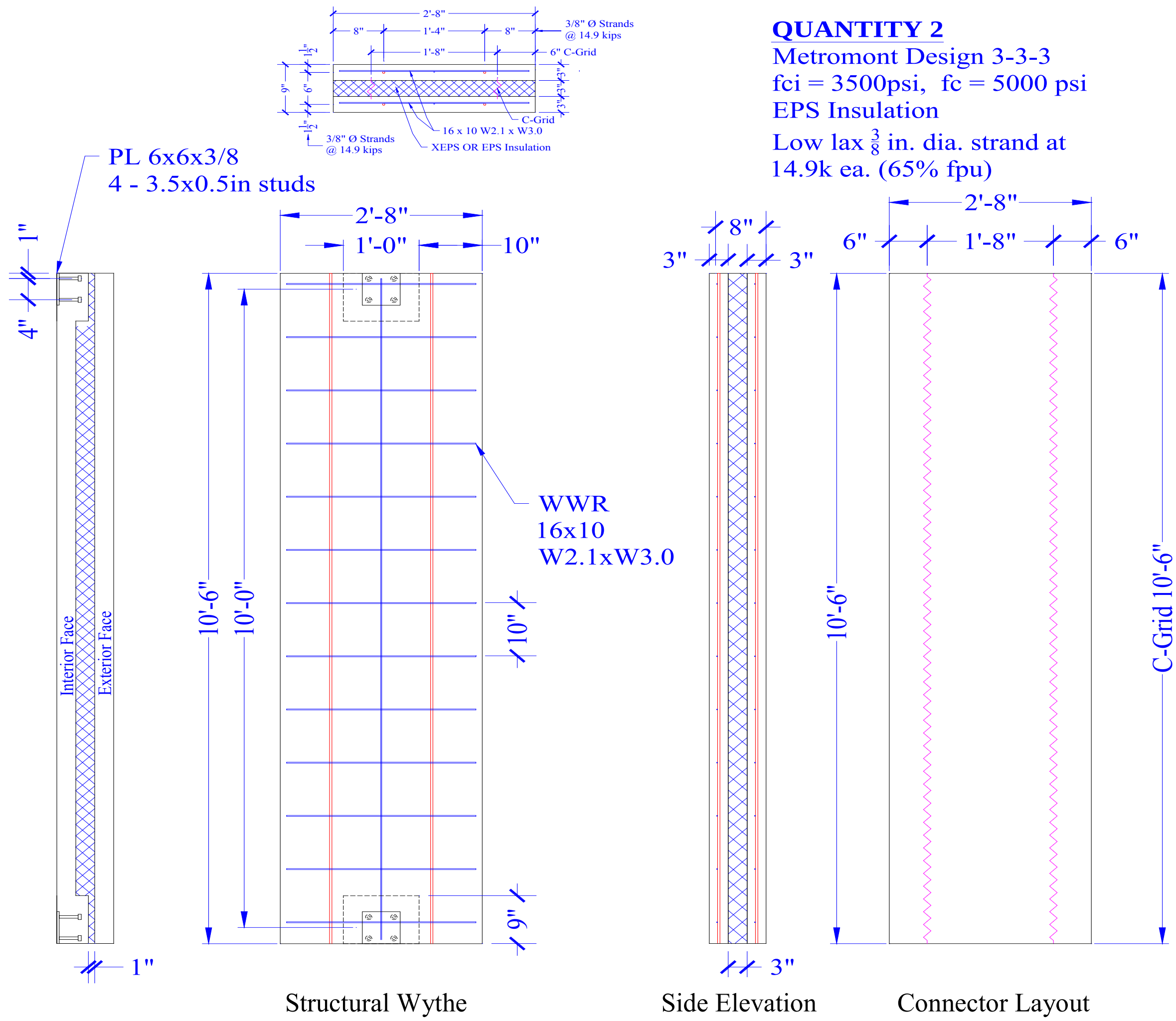


**Figure 25. Specimen PCS10—Top Connection**



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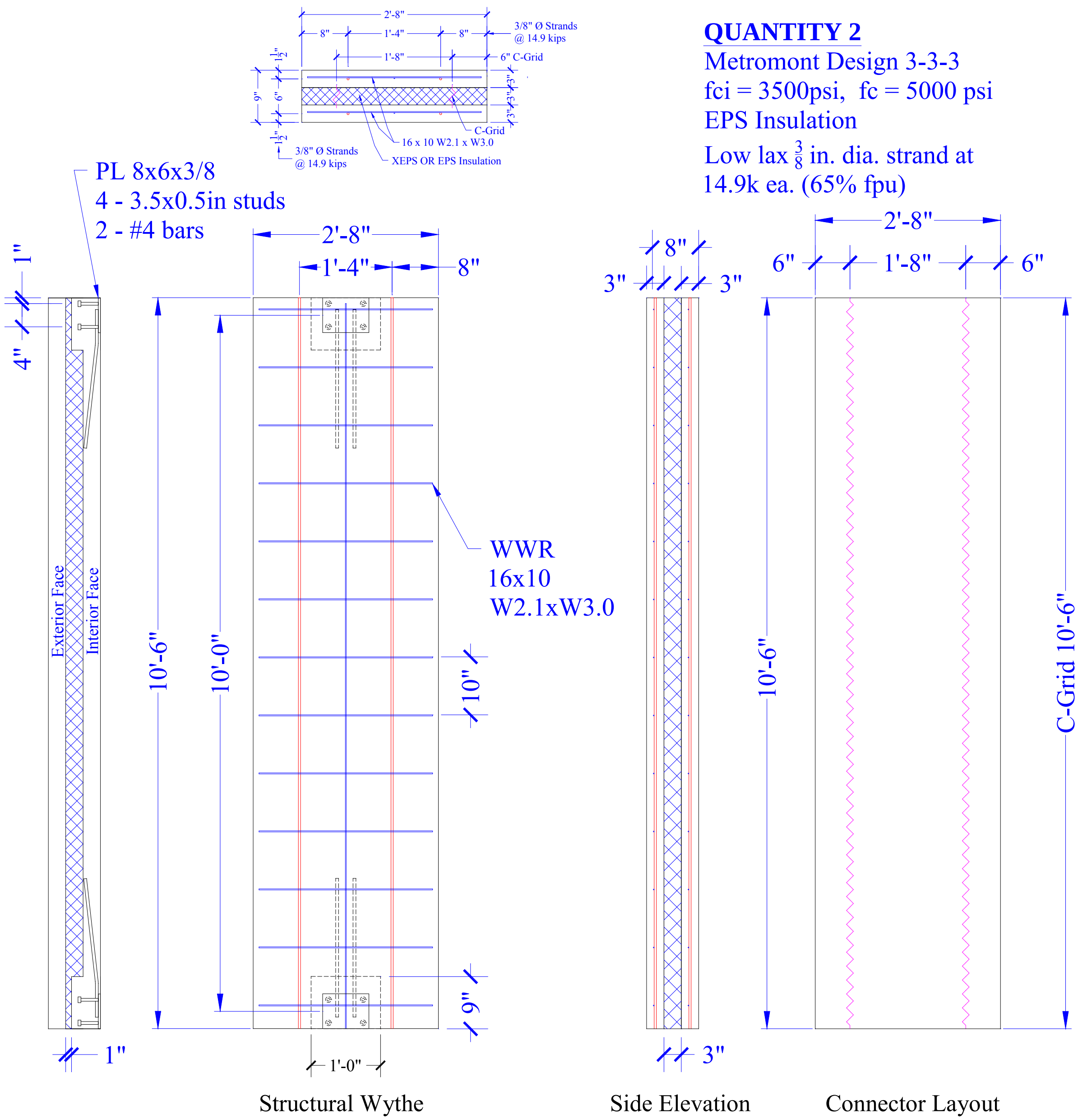


**Figure 26. Specimen PCS11—Base Connection**

For each set of connection panels one panel was tested with the connection in compression and the other in tension. This allowed for an assessment of the performance under both positive phase response and rebound response as shown in Figure 27. The connection details and the welding requirements for the connectors are presented in Figures 28 and 29. The connectors are made out of ASTM A36 plate material and ASTM A706 reinforcement. The embeds were connected to the reaction frame using structural angles. The detail used in both PCS10 and 11 is illustrated in Figure 30.


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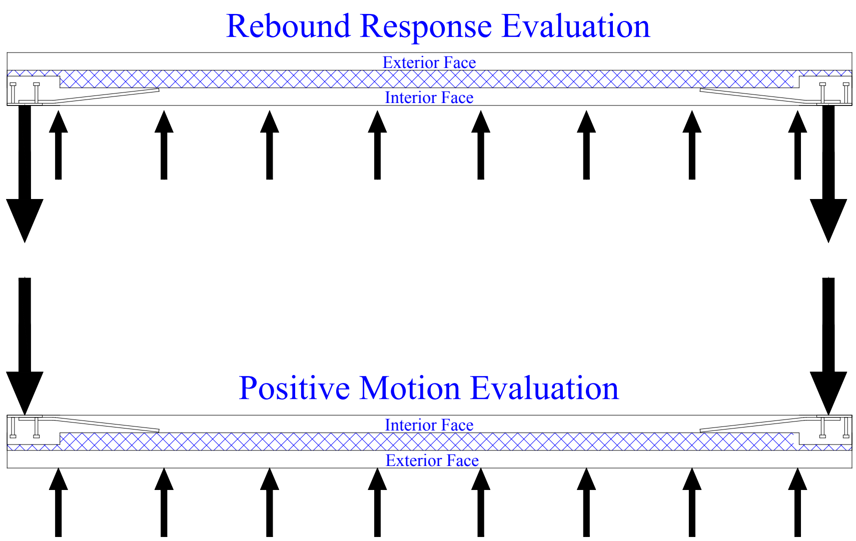


**Figure 27. Connection Loading Plan**

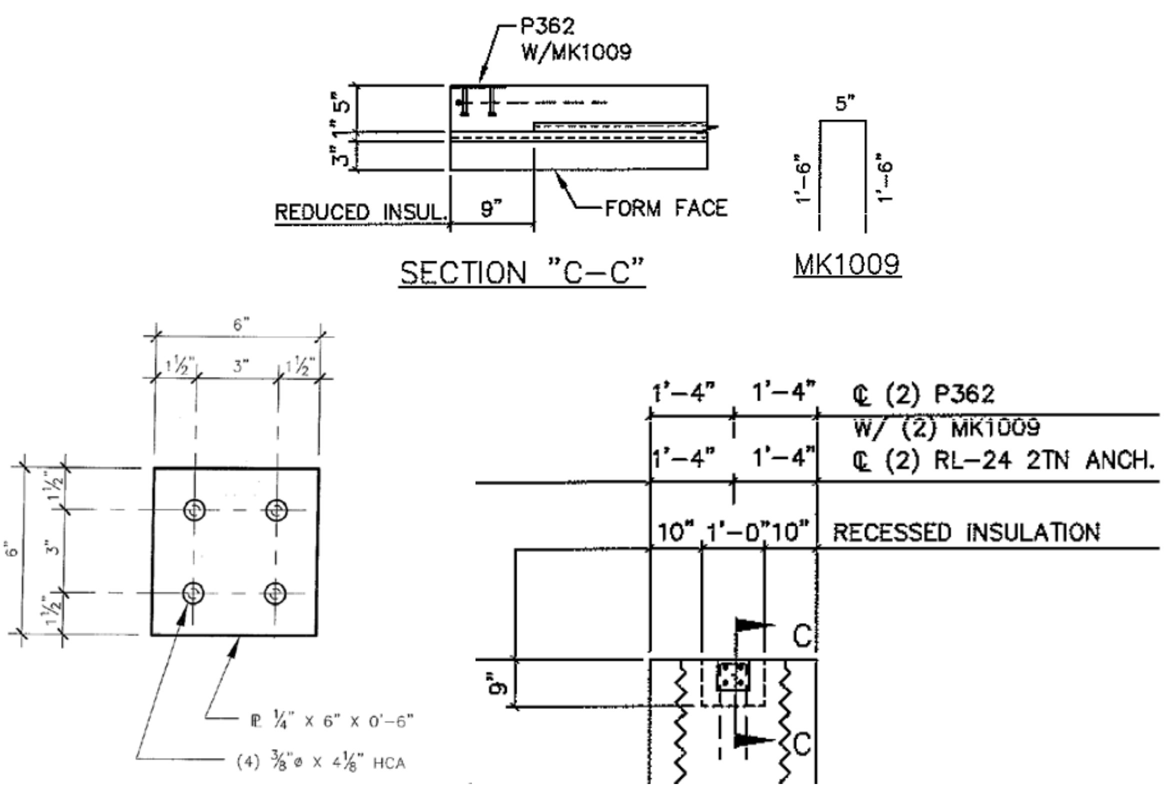


**Figure 28. PCS10 Connection Details**


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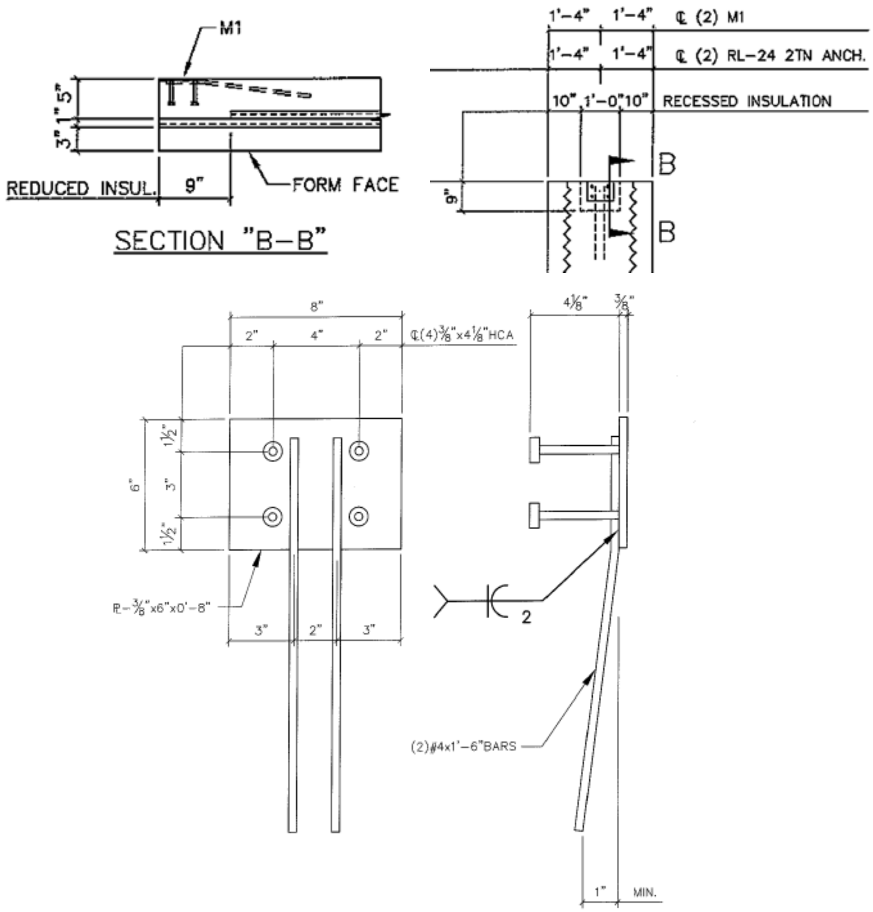


**Figure 29. PCS11 Connection Details**

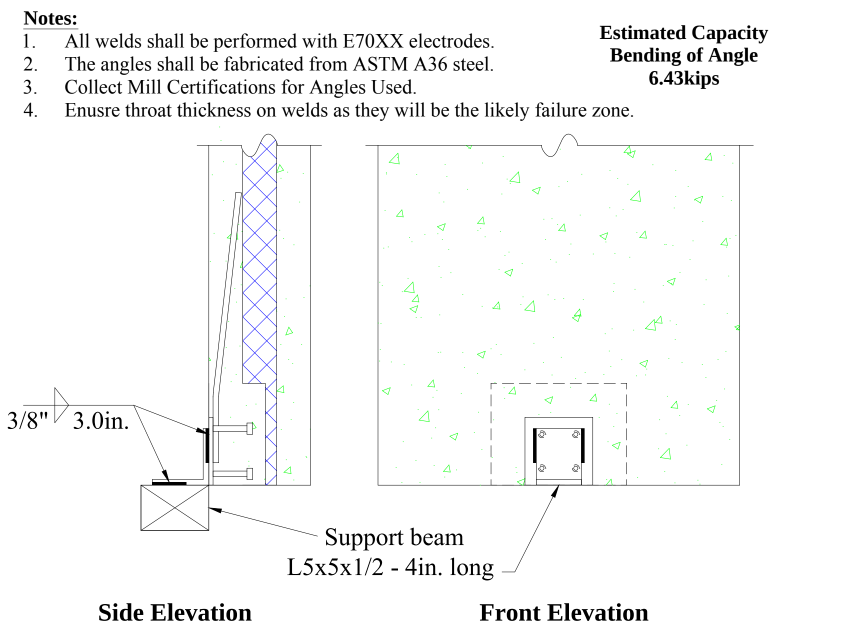


**Figure 30. Embed to Support Connection Detail (PCS10 and 11)**



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## 4.4. As-built Properties

The location of the reinforcement was measured in each panel post-test. The locations are summarized in Table 6.

**Table 6. As-built Reinforcement Locations**

| Sample | Cut Location | | Eastern Half Reinf. Depth | | Western Half Reinf. Depth | |
|---|---|---|---|---|---|---|
| | | | Int. Wythe | Ext. Wythe | Int. Wythe | Ext. Wythe |
| PCS1-A | Near quarter points | | 1 9/16 | 1 9/16 | 1 3/4 | 1 1/2 |
| PCS1-B | 12 in inside quarter points | | 1 13/16 | 1 5/8 | 1 3/4 | 1 5/8 |
| PCS1-C | 10 in from midspan | | 1 3/4 | 1 5/8 | 1 5/8 | 1 1/2 |
| PCS2-A | 10 in inside pick points | | 1 11/16 | 1 7/16 | 1 3/4 | 1 1/2 |
| PCS2-B | Near quarter points | | 1 7/8 | 1 1/2 | 2 | 1 1/2 |
| PCS2-C | 6 in inside pick points | | 1 7/8 | 1 9/16 | 1 15/16 | 1 1/2 |
| PCS3-A | 15 in from midspan | | 2 3/8 | 1 1/2 | 2 1/2 | 1 7/8 |
| PCS3-B | 6 in inside pick points | | 1 3/4 | 1 5/8 | 1 3/4 | 1 5/8 |
| PCS3-C | 12 in pick points | | 2 1/4 | 1 3/8 | 2 | 1 3/8 |
| PCS3-D | 12 in inside pick points | Rebar: | 2 | 1 3/8 | 1 7/8 | 1 1/2 |
| | | Strand: | 1 5/8 | 1 9/16 | 1 5/8 | 1 9/16 |
| PCS3-E | 11 in from midspan | Rebar: | 2 | 1 1/2 | 1 7/8 | 1 3/4 |
| | | Strand: | 2 1/8 | 1 3/8 | 2 7/8 | 1 5/8 |
| PCS3-F | 11 in inside pick points | Rebar: | 1 7/8 | 1 5/8 | 1 7/8 | 1 5/8 |
| | | Strand: | 2 1/4 | 1 1/2 | 2 1/8 | 1 1/2 |
| PCS4-A | 11 in inside quarter points | | 1 3/4 | 1 3/8 | 1 7/8 | 1 1/4 |
| PCS4-B | 18 in from midspan | | 1 13/16 | 1 1/2 | 1 5/8 | 1 1/2 |
| PCS4-C | 10 in from midspan | | 1 3/4 | 1 11/16 | 1 7/8 | 1 3/4 |
| PCS5-A | 6 in from midspan | | 1 15/16 | 1 3/8 | 1 15/16 | 1 1/4 |
| PCS5-B | 11 in from midspan | | 1 3/4 | 1 1/8 | 1 3/4 | 1 1/4 |
| PCS5-C | 12 in from midspan | | 1 7/8 | 1 1/2 | 1 13/16 | 1 1/2 |
| PCS 6-A | 10 in inside pick points | | 1 11/16 | 1 5/8 | 1 3/4 | 1 5/8 |
| PCS6-B | 12 in from midspan | | 1 7/8 | 1 3/8 | 1 7/8 | 1 11/16 |
| PCS6-C | 12 in inside pick points | | 1 3/4 | 1 5/8 | 1 13/16 | 1 11/16 |
| PCS7-A | 11 in from midspan | | 1 13/16 | 1 5/16 | 1 7/8 | 1 1/4 |
| PCS7-B | 10 in from midspan | | 2 | 1 9/16 | 2 1/8 | 1 1/2 |
| PCS7-C | 6 in inside quarter points | | 1 13/16 | 1 5/8 | 1 5/8 | 1 9/16 |
| PCS8-A | 6 in from midspan | | 1 13/16 | 1 5/16 | 1 13/16 | 1 3/16 |
| PCS8-B | 12 in inside pick point | | 1 7/8 | 1 1/4 | 1 3/4 | 1 3/16 |
| PCS8-C | 11 in from midspan | | 1 7/8 | 1 1/4 | 1 13/16 | 1 5/16 |
| PCS9-A | 15 in from midspan | | 1 9/16 | 1 5/8 | 1 3/4 | 1 1/2 |
| PCS9-B | 12 in E of midspan, 21 in W of midspan | | 1 5/8 | 1 5/8 | 1 3/4 | 1 5/8 |
| PCS9-C | 12 in from midspan | | 1 5/8 | 1 1/2 | 1 1/2 | 1 5/8 |
| PCS10-A IN | 6 in inside pick points | | 1 11/16 | 1 1/2 | 1 5/8 | 1 1/2 |
| PCS10-B OUT | 8 in outside of pick points | | 1 15/16 | 1 3/8 | 1 7/8 | 1 3/8 |
| PCS11-A IN | 6 in inside pick points | | 1 11/16 | 1 1/2 | 1 5/8 | 1 1/2 |
| PCS11-B OUT | 6 in inside pick points | | 1 1/2 | 1 3/4 | 1 1/2 | 1 13/16 |


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## 5. EXPERIMENTAL SETUP

All panels were loaded to failure using a loading tree fixture. The fixture applied loads at discrete points along the panel to generate an approximate uniform load. The point loads were applied through balanced pins that allowed rotation of the individual loading arms. The result was an approximate uniform load along the span. The single-span fixture is illustrated in Figures 31 and 32. The end connections on the singles span panels consisted of a heavy-wall steel pipe. These connections were idealized as rollers.

The two-span fixture is illustrated in the schematic shown in Figures 33 and 34. Similar supports were used at the ends of the panel. The midspan connection consisted of a welded detail similar to connections used in the building structure.

The foundation and top floor connections were examined by fabricating the panel with the same connection on both ends. Using the same connection on each end precluded the possibility of a non-symmetric failure mode. The connections were examined for both inbound and rebound response. The setup used is illustrated in Figure 35.

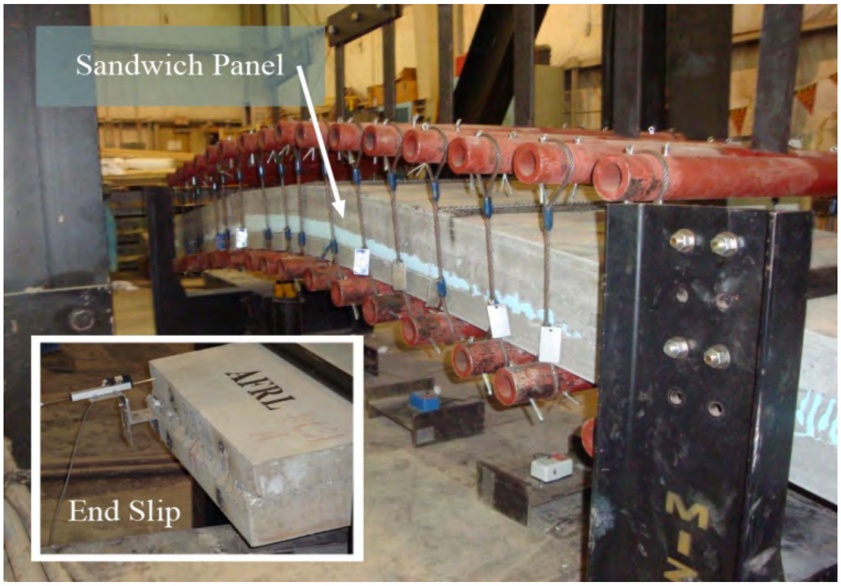


**Figure 31. Single-span Loading Tree**

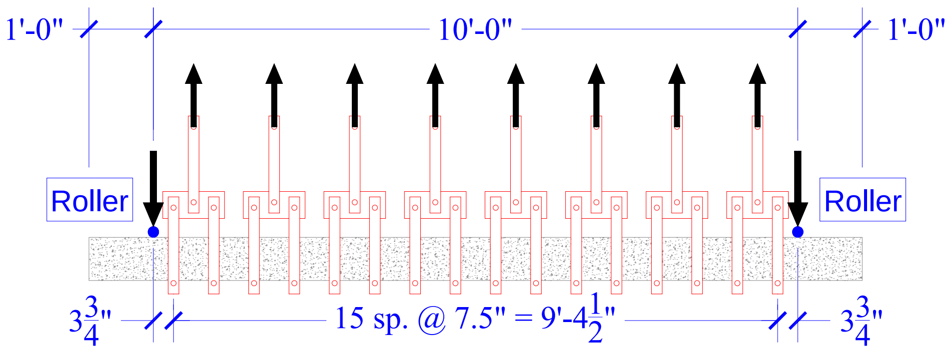


**Figure 32. Single-span Loading Tree Schematic**


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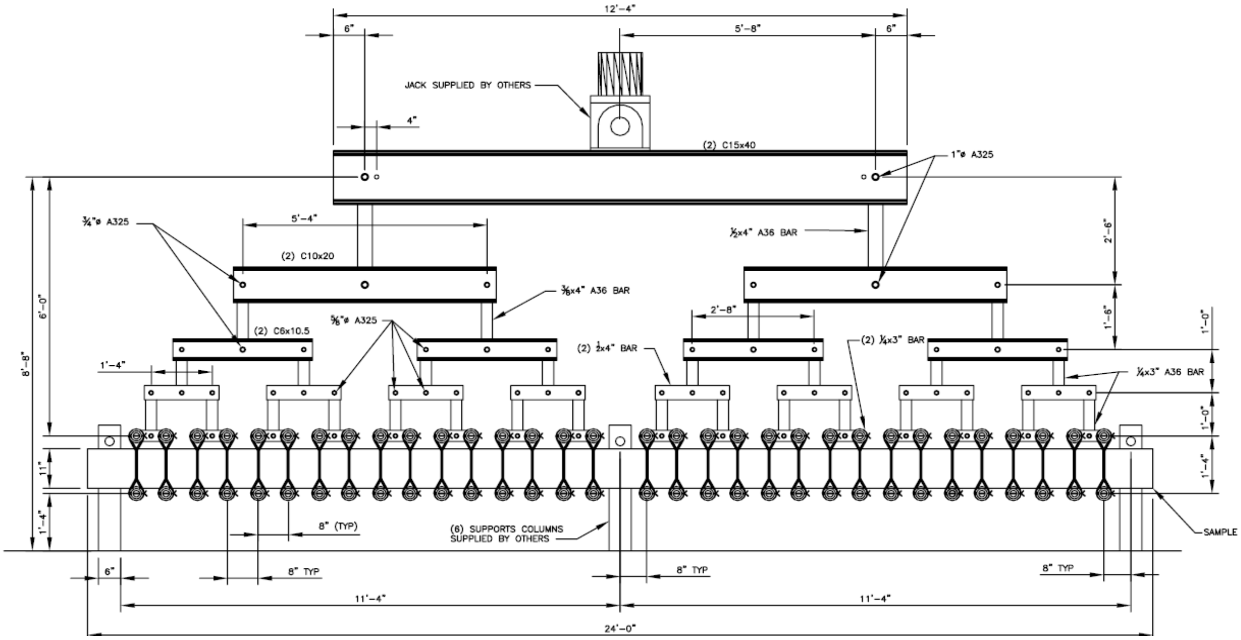


**Figure 33. Two-span Loading Tree**

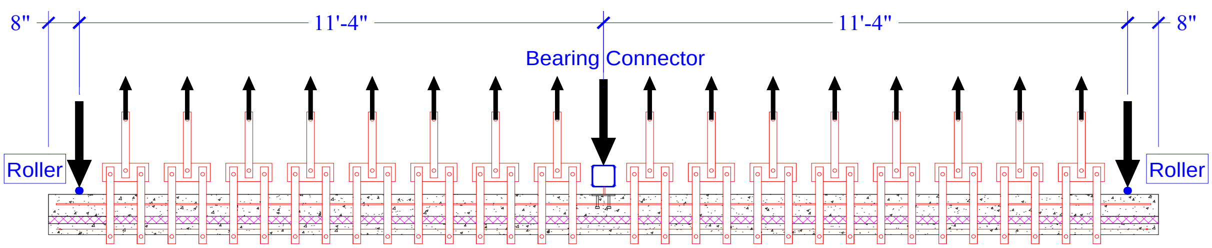


**Figure 34. Schematic of Single and Two-span Fixtures**

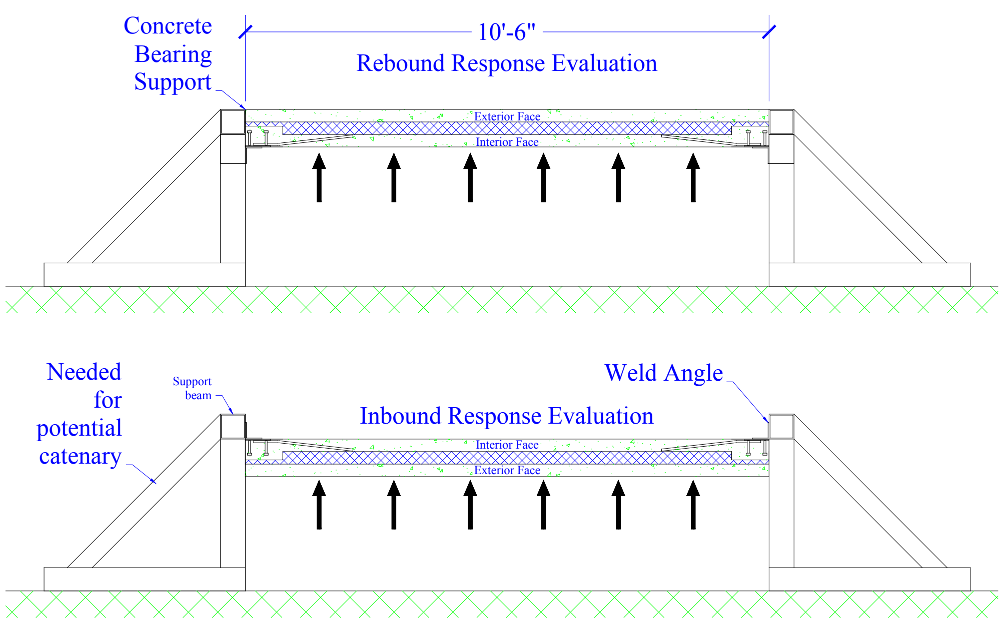


**Figure 35. Schematic of End Connection Setup**


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All specimens were tested in a quasi-static manner at a displacement rate of approximately 0.01 in/sec.

## 5.1. Instrumentation

Displacements, force and video were recorded for each experiment. The applied load was measured using a load cell in line with the hydraulic actuator. The pressure demand was computed from the measured load by dividing it by the surface area of the specimen. The displacements were measured at mid span and at quarter points of each panel. For the two-span panels the midspan and quarter point displacements were measured on each span. The displacement measurement locations are illustrated in Figure 36.

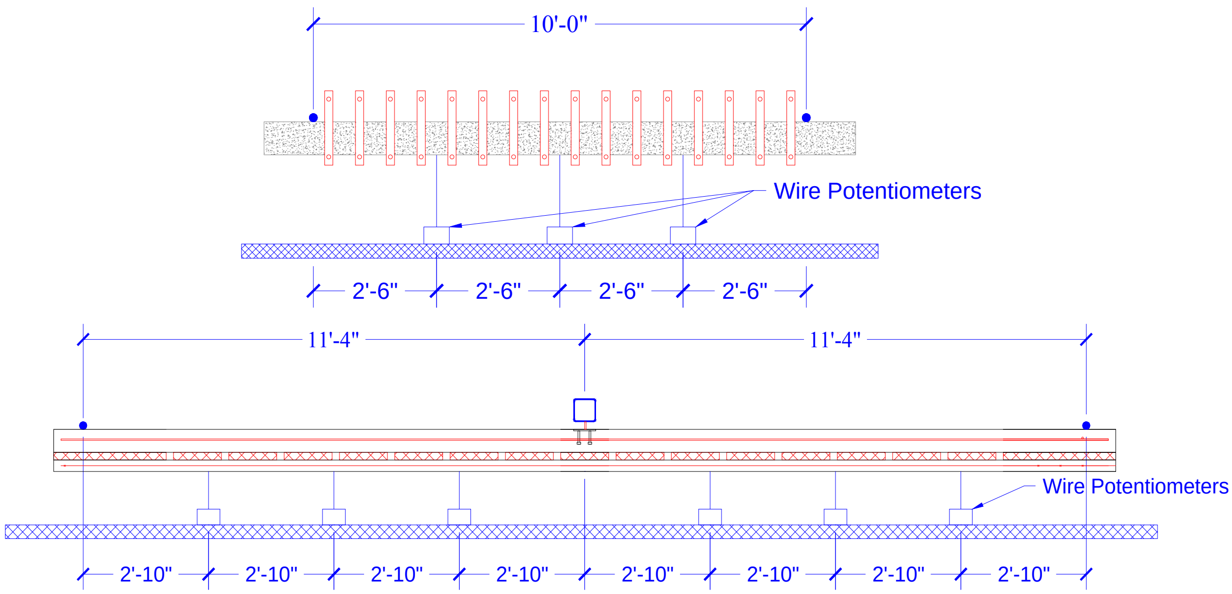


**Figure 36. Displacement Instrumentation**

To correlate the shear displacement of the shear ties with the failure modes of the panels, the relative deformation of the wythes was measured at each end of the panel. A linear voltage displacement transducer was connected to the exterior wythe, and the relative end slip of the interior wythe was measured as illustrated in Figure 37.


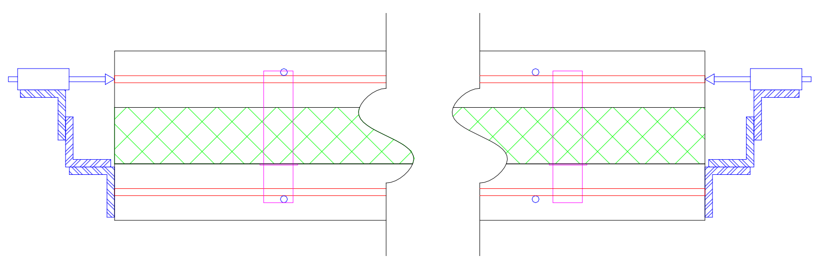

**Figure 37. End Shear Instrumentation**


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## 5.2. Material Properties

To correlate the material strengths with that of the wall systems, the reinforcement and concrete materials were evaluated. Tensile testing of steel reinforcement samples delivered with the specimens was conducted when material was available. When material was not available, the mill certification data of the steel were noted. The elastic modulus, yield stress, ultimate stress, fracture strain, and a full stress–strain curve were determined for each test. Concrete properties were evaluated in accordance with ASTM C39. In addition, flexural strength tensile tests of the concrete were conducted in accordance with ASTM C293.

## 5.3. Reinforcement Materials

The specimens were reinforced with a combination of WWR, deformed reinforcing steel, and seven-wire prestressing strand. The reinforcement used in the study conformed to the following specifications.

- *Welded Wire Reinforcement*: ASTM A82
- *Deformed Reinforcement*: ASTM A615 Grade 60 or ASTM A706
- *Prestressing Reinforcement:* Seven Wire 3/8-in diameter low-relaxation strand meeting the requirements of ASTM A416.

The allowable tensile properties of the reinforcement are provided in Table 7. The tensile properties of the material used in the specimens are summarized in Table 8.

**Table 7. Material Limits**

| Material | Yield Stress [ksi] | Tensile Strength [ksi] | Ultimate Strain |
|---|---|---|---|
| ASTM A82 | 65 (min) | 75 (min) 1.25 fy (min) | No Requirement |
| ASTM A615 | 60 (min) | 90 (min) | 0.09 (min) |
| ASTM A706 | 60 (min) 78 (max) | 80 (min) | 0.014 (min) |
| ASTM A416 | 0.90 fpu (min) | 270 (min) | 0.035 (min) |

**Table 8. Mill Certified Reinforcement Properties of Specimens**

| Specimen | Fabricator | Reinforcing Material | ASTM Method | Yield Stress [ksi] | Tensile Strength [ksi] | Ultimate Strain |
|---|---|---|---|---|---|---|
| PCD1, PCS4, PCS5, PCS7, PCS8, | Coreslab | #3 bar | A615 | 69.55 | 111.6 | 0.15 |
| | | #4 bar | A615 | 67.60 | 104.8 | 0.12 |
| | | #5 bar | A706 | 63.00 | 94.60 | 0.15 |
| | | 3/8-in strand | A416 | 258.08 | 281.68 | 0.07 |
| PCD2, PCS1, PCS2, PCS3, PCS6, PCS9 | Metromont | #5 bar | NA | NA | NA | NA |
| | | WWR | NA | NA | NA | NA |
| | | 3/8-in strand | NA | NA | NA | NA |
| TS1, TS2, TS3 | TCA | 6×6 W2.9×W2.9 | A185 | NA | 106.07 | NA |
| | | #3 bar | A615 | 67.80 | 105.30 | 0.12 |
| Tin1, Tin2 | Tindall | #3 bar | A615 | 60 | NA | NA |
| | | 3/8-in strand | A416 | NA | 270 | NA |


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### 5.4. Concrete Material Properties

The static specimens were fabricated in accordance with current construction practices. Ready mix concrete with a specified 28-day compressive strength of 4000 psi was used for the tilt-up construction. Plant-batched concrete with a minimum compressive strength of 3500 psi at transfer of prestress and 5000 psi at 28 days was specified. The static wall specimens were tested over a period of seven months. To assess the concrete strength of each wall specimen at the date of the experiment, concrete cylinders were periodically tested to failure in accordance with ASTM C39. Due to the enormity of wall specimens and the duration of the experimental program, cylinders could not be tested along with each panel. Instead the cylinder tests were conducted at various stages throughout the research program. The discrete cylinder test results were used to develop a strength gain curve that was used to estimate the strength of the concrete at each experiment date.

The batching properties for the concrete used for each specimen are summarized in Table 9. The approximate concrete compressive strengths at the day of testing are summarized in Table 10.

**Table 9. Concrete Batching Properties of Specimens**

| Specimen | Use | Cement | Additional Cementitious Material | w/c Ratio | Unit Weight [pcf] | Slump [in] |
|---|---|---|---|---|---|---|
| PCD1, PCS4, PCS5, PCS7, PCS8, | Both Wythes | Type III | None | 0.394 | 144.28 | 9.0 |
| PCD2, PCS1, PCS2, PCS3, PCS6, PCS9 | Both Wythes | NA | NA | NA | NA | NA |
| TS1, TS2, TS3 | Exterior Wythe | Type I | Fly Ash | 0.385 | 150.0 | 3.25 |
| | Interior Wythe | Type I | Fly Ash | 0.390 | 148.4 | 4.50 |

The concrete modulus of rupture was measured for the TCA specimens in accordance with ASTM C293. Modulus of rupture tests were not conducted on the other specimen concrete. The results for the TCA panels are summarized in Table 11.


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**Table 10. Concrete Compressive Strength of Specimen [psi]**

| Specimen | Age at Test [days] | Est. $f'_c$ Structural Wythe | Est. $f'_c$ Exterior Wythe | Specimen | Age at Test [days] | Est. $f'_c$ Structural Wythe | Est. $f'_c$ Exterior Wythe |
|---|---|---|---|---|---|---|---|
| TS1-A | 21 | 4907 | 5499 | PCS9-A | 37 | 8564 | 8564 |
| TS1-B | 22 | 4947 | 5539 | PCS9-B | 41 | 8650 | 8650 |
| TS1-C | 21 | 4907 | 5499 | PCS9-C | 41 | 8650 | 8650 |
| Average | | 4920 | 5512 | Average | | 8621 | 8621 |
| TS2-A | 22 | 4947 | 5539 | PCS10-A | 72 | 9322 | 9322 |
| TS2-B | 21 | 4907 | 5499 | PCS10-B | 85 | 9604 | 9604 |
| TS2-C | 22 | 4947 | 5539 | Average | | 9463 | 9463 |
| Average | | 4933 | 5526 | PCS11-A | 72 | 9322 | 9322 |
| PCS1-A | 20 | 8195 | 8195 | PCS11-B | 86 | 9626 | 9626 |
| PCS1-B | 21 | 8217 | 8217 | Average | | 9474 | 9474 |
| PCS1-C | 22 | 8238 | 8238 | PCS3-D | 36 | 8542 | 8542 |
| Average | | 8217 | 8217 | PCS3-E | 43 | 8694 | 8694 |
| PCS2-A | 23 | 8260 | 8260 | PCS3-F | 43 | 8694 | 8694 |
| PCS2-B | 23 | 8260 | 8260 | Average | | 8643 | 8643 |
| PCS2-C | 42 | 8672 | 8672 | PCD1-A | 60 | 9228 | 9228 |
| Average | | 8397 | 8397 | PCD1-B | 63 | 9201 | 9201 |
| PCS3-A | 22 | 8238 | 8238 | PCD1-C | 64 | 9192 | 9192 |
| PCS3-B | 26 | 8325 | 8325 | Average | | 9207 | 9207 |
| PCS3-C | 41 | 8650 | 8650 | PCD2-A | 28 | 8369 | 8369 |
| Average | | 8405 | 8405 | PCD2-B | 29 | 8390 | 8390 |
| PCS4-A | 100 | 8873 | 8873 | PCD2-C | 30 | 8412 | 8412 |
| PCS4-B | 109 | 8793 | 8793 | Average | | 8390 | 8390 |
| PCS4-C | 109 | 8793 | 8793 | TS3-A | 128 | 5766 | 6355 |
| Average | | 8820 | 8820 | TS3-B | 132 | 5772 | 6361 |
| PCS5-A | 101 | 8864 | 8864 | Average | | 5769 | 6358 |
| PCS5-B | 112 | 8766 | 8766 | TS3-C | 126 | 5763 | 6352 |
| PCS5-C | 113 | 8757 | 8757 | TS3-D | 127 | 5765 | 6353 |
| Average | | 8796 | 8796 | Average | | 5764 | 6352 |
| PCS6-A | 37 | 8564 | 8564 | TS3-E | 136 | 5778 | 6366 |
| PCS6-B | 45 | 8737 | 8737 | TS3-F | 140 | 5783 | 6371 |
| PCS6-C | 45 | 8737 | 8737 | Average | | 5781 | 6369 |
| Average | | 8679 | 8679 | Tin1 – A | 95 | 8214 | 8214 |
| PCS7-A | 106 | 8820 | 8820 | Tin1 – B | 99 | 8275 | 8275 |
| PCS7-B | 106 | 8820 | 8820 | Tin1 – C | 204 | 8627 | 8627 |
| PCS7-C | 94 | 8926 | 8926 | Average | | 8451 | 8451 |
| Average | | 8855 | 8855 | Tin2 –A | 94 | 8199 | 8199 |
| PCS8-A | 101 | 8864 | 8864 | Tin2 –B | 101 | 8306 | 8306 |
| PCS8-B | 108 | 8802 | 8802 | Tin2 –C | 225 | 8627 | 8627 |
| PCS8-C | 108 | 8802 | 8802 | Average | | 8466 | 8466 |
| Average | | 8823 | 8823 | | | | |

**Table 11. As-built Concrete Tensile Properties**

| Wythe | Panel Type | Compressive Strength Average [ksi] | Modulus of Rupture | |
|---|---|---|---|---|
| | | | Average [ksi] | $x$ sqrt($f'_c$) |
| Structural | TS1, TS2 | 4650 | 564.5 | 8.28 |
| Non-Structural | | 5110 | 622.2 | 8.70 |


Distribution Statement A: Approved for public release; distribution unlimited.

# 6. EXPERIMENTAL RESULTS FOR SINGLE-SPAN PANELS

A series of 14 PC CSW panels typical of PCI and TCA production were designed. Three specimens of each type of panel were fabricated and tested to failure. The longitudinal reinforcement was varied between reinforcing steel, prestressing steel, and WWR. The tie type and insulation type were varied. The three cross-section types tested were 6-2-3, 3-2-3 and 3-3-3. A summary of each panel type and the results of the tests are presented in this chapter. Included in each section is a summary of the material properties, reinforcement details, load-deformation response, inter-wythe slip (if measured), and ultimate strength. A summary of the fabrication properties and results are included in Tables 12 and 13.

**Table 12. Single-span Fabrication Summary**

| ID | Configuration | Insulation | Reinforcement | Ties | Designer | Fabricator | Fabricated | Age at Test [days] |
|---|---|---|---|---|---|---|---|---|
| TS1-A | 6-2-3 | XPS | R.C. | THERMOMASS® - NC | TCA | LJB Inc. | 9/23/2008 | 21 |
| TS1-B | 6-2-3 | XPS | R.C. | THERMOMASS® - NC | TCA | LJB Inc. | 9/23/2008 | 22 |
| TS1-C | 6-2-3 | XPS | R.C. | THERMOMASS® - NC | TCA | LJB Inc. | 9/23/2008 | 21 |
| TS2-A | 3-2-3 | XPS | R. C. | THERMOMASS® - Comp | TCA | LJB Inc. | 9/23/2008 | 22 |
| TS2-B | 3-2-3 | XPS | R. C. | THERMOMASS® - Comp | TCA | LJB Inc. | 9/23/2008 | 21 |
| TS2-C | 3-2-3 | XPS | R. C. | THERMOMASS® - Comp | TCA | LJB Inc. | 9/23/2008 | 22 |
| PCS1-A | 3-2-3 | EPS | PS/WWR | Steel C-clips | Metromont | Metromont | 2/10/2009 | 20 |
| PCS1-B | 3-2-3 | EPS | PS/WWR | Steel C-clips | Metromont | Metromont | 2/10/2009 | 21 |
| PCS1-C | 3-2-3 | EPS | PS/WWR | Steel C-clips | Metromont | Metromont | 2/10/2009 | 22 |
| PCS2-A | 3-2-3 | EPS | PS/WWR | C-Grid© | Metromont | Metromont | 2/10/2009 | 23 |
| PCS2-B | 3-2-3 | EPS | PS/WWR | C-Grid© | Metromont | Metromont | 2/10/2009 | 23 |
| PCS2-C | 3-2-3 | EPS | PS/WWR | C-Grid© | Metromont | Metromont | 2/10/2009 | 42 |
| PCS3-A | 3-2-3 | EPS | Rebar/WWR | C-Grid© | Metromont | Metromont | 2/11/2009 | 22 |
| PCS3-B | 3-2-3 | EPS | Rebar/WWR | C-Grid© | Metromont | Metromont | 2/11/2009 | 26 |
| PCS3-C | 3-2-3 | EPS | Rebar/WWR | C-Grid© | Metromont | Metromont | 2/11/2009 | 41 |
| PCS3-D | 3-2-3 | EPS | PS&Rebar/WWR | C-Grid© | Metromont | Metromont | 2/10/2009 | 36 |
| PCS3-E | 3-2-3 | EPS | PS&Rebar/WWR | C-Grid© | Metromont | Metromont | 2/10/2009 | 43 |
| PCS3-F | 3-2-3 | EPS | PS&Rebar/WWR | C-Grid© | Metromont | Metromont | 2/10/2009 | 43 |
| PCS4-A | 3-3-3 | XPS | PS/Rebar | Galvanized Steel C-clips | Coreslab | Coreslab | 12/15/2008 | 100 |
| PCS4-B | 3-3-3 | XPS | PS/Rebar | Steel C-clips | Coreslab | Coreslab | 12/15/2008 | 109 |
| PCS4-C | 3-3-3 | XPS | PS/Rebar | Steel C-clips | Coreslab | Coreslab | 12/15/2008 | 109 |
| PCS5-A | 3-3-3 | XPS | PS/Rebar | THERMOMASS® - Comp | Coreslab | Coreslab | 12/15/2008 | 101 |
| PCS5-B | 3-3-3 | XPS | PS/Rebar | THERMOMASS® - Comp | Coreslab | Fabricator | 12/15/2008 | 112 |
| PCS5-C | 3-3-3 | XPS | PS/Rebar | THERMOMASS® - Comp | Coreslab | Coreslab | 12/15/2008 | 113 |
| PCS6-A | 3-3-3 | XPS | PS/WWR | C-Grid© | Metromont | Metromont | 2/10/2009 | 37 |
| PCS6-B | 3-3-3 | XPS | PS/WWR | C-Grid© | Metromont | Metromont | 2/10/2009 | 45 |
| PCS6-C | 3-3-3 | XPS | PS/WWR | C-Grid© | Metromont | Metromont | 2/10/2009 | 45 |
| PCS7-A | 3-3-3 | XPS | Rebar | THERMOMASS® - Comp | Coreslab | Coreslab | 12/15/2008 | 106 |
| PCS7-B | 3-3-3 | XPS | Rebar | THERMOMASS® - Comp | Coreslab | Coreslab | 12/15/2008 | 106 |
| PCS7-C | 3-3-3 | XPS | Rebar | THERMOMASS® - Comp | Coreslab | Coreslab | 12/15/2008 | 94 |
| PCS8-A | 3-3-3 | PIMA | PS/Rebar | THERMOMASS® - Comp | Coreslab | Coreslab | 12/15/2008 | 101 |
| PCS8-B | 3-3-3 | PIMA | PS/Rebar | THERMOMASS® - Comp | Coreslab | Coreslab | 12/15/2008 | 108 |
| PCS8-C | 3-3-3 | PIMA | PS/Rebar | THERMOMASS® - Comp | Coreslab | Coreslab | 12/15/2008 | 108 |
| PCS9-A | 3-3-3 | PIMA | PS/WWR | C-Grid© | Metromont | Metromont | 2/10/2009 | 37 |
| PCS9-B | 3-3-3 | PIMA | PS/WWR | C-Grid© | Metromont | Metromont | 2/10/2009 | 41 |
| PCS9-C | 3-3-3 | PIMA | PS/WWR | C-Grid© | Metromont | Metromont | 2/10/2009 | 41 |
| Tin1-A | 3-4-3 | XPS | PS/Rebar | MB Truss Girder | Tindall | Tindall | 8/3/09 | 95 |
| Tin1-B | 3-4-3 | XPS | PS/Rebar | MB Truss Girder | Tindall | Tindall | 8/3/09 | 99 |
| Tin1-C | 3-4-3 | XPS | PS/Rebar | MB Truss Girder | Tindall | Tindall | 8/3/09 | 204 |
| Tin2-A | 3-4-3 | XPS | PS/Rebar | MB Truss Girder | Tindall | Tindall | 8/3/09 | 94 |
| Tin2-B | 3-4-3 | XPS | PS/Rebar | MB Truss Girder | Tindall | Tindall | 8/3/09 | 101 |
| Tin2-C | 3-4-3 | XPS | PS/Rebar | MB Truss Girder | Tindall | Tindall | 8/3/09 | 225 |


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## Table 13. Single-span Results Summary

| Specimen | Est. Conc. $f'_c$ Struct. | Est. Conc. $f'_c$ Ext. | Max Load [lbs] | Max Pressure [psi] | Corresponding Displacement [in] | East Slip [in] | West Slip [in] | Rotation [deg] | Measured Moment Capacity [k-in] | $d_{top}$ | $d_{bot}$ | Estimated Composite Capacity [k-in] | Estimated Non-Composite Capacity [k-in] | % Composite | Max Reaction [lbs] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TS1-A | 4907 | 5499 | 6508 | 3.389 | 5.319 | NA | NA | 5.086 | 97.614 | 1.604 | 8.125 | 149.704 | 40.807 | 52% | 3,254 |
| TS1-B | 4947 | 5539 | 4918 | 2.561 | 6.212 | NA | NA | 5.943 | 73.768 | 1.958 | 7.688 | 143.297 | 35.280 | 36% | 2,459 |
| TS1-C | 4907 | 5499 | 6450 | 3.359 | 3.613 | NA | NA | 3.452 | 96.749 | 1.875 | 7.813 | 145.239 | 36.873 | 55% | 3,225 |
| Average | 4920 | 5512 | 5958 | 3.10 | 5.05 | NA | NA | 4.83 | 89.4 | 1.813 | 7.875 | 146.080 | 37.653 | 48% | 2979 |
| TS2-A | 4947 | 5539 | 8020 | 4.177 | 4.925 | NA | NA | 4.708 | 120.30 | 1.625 | 6.313 | 121.529 | 20.149 | 99% | 4,010 |
| TS2-B | 4907 | 5499 | 8210 | 4.276 | 5.047 | NA | NA | 4.825 | 123.146 | 1.719 | 6.344 | 123.825 | 21.109 | 99% | 4,105 |
| TS2-C | 4947 | 5539 | 8020 | 4.177 | 5.918 | NA | NA | 5.660 | 120.305 | 1.500 | 6.313 | 119.800 | 19.230 | 101% | 4,010 |
| Average | 4933 | 5526 | 8083 | 4.21 | 5.30 | NA | NA | 5.06 | 121.3 | 1.615 | 6.323 | 121.718 | 20.163 | 100% | 4042 |
| PCS1-A | 8195 | 8195 | 17728 | 4.617 | 1.712 | 0.144 | 0.142 | 1.635 | 265.92 | 1.5313 | 6.3438 | 296.1 | 129.54 | 82% | 8,864 |
| PCS1-B | 8217 | 8217 | 17693 | 4.608 | 2.010 | 0.134 | 0.187 | 1.919 | 265.39 | 1.6250 | 6.2188 | 296.1 | 129.54 | 82% | 8,846 |
| PCS1-C | 8238 | 8238 | 16399 | 4.271 | 1.832 | 0.126 | 0.195 | 1.749 | 245.98 | 1.5625 | 6.3125 | 296.1 | 129.54 | 70% | 8,199 |
| Average | 8217 | 8217 | 17273 | 4.50 | 1.85 | 0.13 | 0.17 | 1.77 | 259.1 | 1.5730 | 6.292 | 296.1 | 129.54 | 78% | 8637 |
| PCS2-A | 8260 | 8260 | 20448 | 5.325 | 1.990 | 0.291 | 0.000 | 1.900 | 306.73 | 1.4688 | 6.2813 | 296.1 | 129.54 | 106% | 10,224 |
| PCS2-B | 8260 | 8260 | 19183 | 4.996 | 2.309 | 0.374 | 0.003 | 2.204 | 287.74 | 1.5000 | 6.0625 | 296.1 | 129.54 | 95% | 9,591 |
| PCS2-C | 8672 | 8672 | 19319 | 5.031 | 1.345 | 0.208 | 0.005 | 1.284 | 289.79 | 1.5313 | 6.0938 | 296.1 | 129.54 | 96% | 9,660 |
| Average | 8397 | 8397 | 19650 | 5.12 | 1.88 | 0.29 | 0.00 | 1.80 | 294.8 | 1.500 | 6.146 | 296.1 | 129.54 | 99% | 9825 |
| PCS3-A | 8238 | 8238 | 21256 | 5.536 | 6.000 | 0.016 | 0.008 | 5.711 | 318.85 | 1.6875 | 5.5625 | 318.88 | 54.933 | 100% | 10,628 |
| PCS3-B | 8325 | 8325 | 16328 | 4.252 | 0.892 | 0.041 | 0.002 | 0.852 | 244.92 | 1.6250 | 6.2500 | 318.88 | 54.933 | 72% | 8,164 |
| PCS3-C | 8650 | 8650 | 23643 | 6.157 | 5.500 | 0.001 | 0.090 | 5.237 | 354.64 | 1.3750 | 5.8750 | 318.88 | 54.933 | 114% | 11,821 |
| Average | 8405 | 8405 | 20409 | 5.31 | 4.13 | 0.02 | 0.03 | 3.93 | 306.1 | 1.563 | 5.896 | 318.88 | 54.933 | 95% | 10205 |
| PCS3-D | 8542 | 8542 | 21886 | 5.699 | 5.544 | 0.695 | 0.368 | 5.279 | 328.28 | 1.4375 | 6.0625 | 318.88 | 54.933 | 104% | 10943 |
| PCS3-E | 8694 | 8694 | 23645 | 6.157 | 5.320 | 0.652 | 0.358 | 5.067 | 354.67 | 1.5625 | 6.3750 | 318.88 | 54.933 | 114% | 11822 |
| PCS3-F | 8694 | 8694 | 20956 | 5.457 | 3.896 | 0.000 | 0.762 | 3.716 | 314.34 | 1.5000 | 6.5000 | 318.88 | 54.933 | 98% | 10478 |
| Average | 8643 | 8643 | 22162 | 5.770 | 4.920 | 0.450 | 0.500 | 4.690 | 332.4 | 1.500 | 6.313 | 318.880 | 54.933 | 105% | 11081 |
| PCS4-A | 8873 | 8873 | 18410 | 4.794 | 6.943 | 0.673 | 0.897 | 6.601 | 276.14 | 1.3125 | 7.1875 | 347.49 | 129.54 | 67% | 9,205 |
| PCS4-B | 8793 | 8793 | 16138 | 4.203 | 5.408 | 0.250 | 0.974 | 5.151 | 242.07 | 1.5000 | 7.2813 | 347.49 | 129.54 | 52% | 8,069 |
| PCS4-C | 8793 | 8793 | 19110 | 4.976 | 6.355 | 0.512 | 0.909 | 6.046 | 286.65 | 1.7188 | 7.1875 | 347.49 | 129.54 | 72% | 9,555 |
| Average | 8820 | 8820 | 17886 | 4.66 | 6.24 | 0.48 | 0.93 | 5.93 | 268.3 | 1.510 | 7.219 | 347.49 | 129.54 | 64% | 8943 |
| PCS5-A | 8864 | 8864 | 17770 | 4.628 | 4.765 | 0.527 | 0.604 | 4.541 | 266.55 | 1.3125 | 7.0625 | 347.49 | 129.54 | 63% | 8,885 |
| PCS5-B | 8766 | 8766 | 19910 | 5.185 | 5.118 | 0.500 | 0.562 | 4.875 | 298.65 | 1.1875 | 7.2500 | 347.49 | 129.54 | 78% | 9,955 |
| PCS5-C | 8757 | 8757 | 18252 | 4.753 | 5.536 | 0.633 | 0.637 | 5.272 | 273.78 | 1.5000 | 7.1563 | 347.49 | 129.54 | 66% | 9,126 |
| Average | 8796 | 8796 | 18644 | 4.86 | 5.14 | 0.55 | 0.60 | 4.90 | 279.7 | 1.333 | 7.156 | 347.490 | 129.54 | 69% | 9322 |
| PCS6-A | 8564 | 8564 | 18581 | 4.839 | 3.644 | 0.502 | 0.504 | 3.475 | 278.71 | 1.6250 | 7.2813 | 347.49 | 129.54 | 68% | 9,290 |
| PCS6-B | 8737 | 8737 | 18146 | 4.726 | 2.945 | 0.443 | 0.236 | 2.810 | 272.19 | 1.5313 | 7.1250 | 347.49 | 129.54 | 65% | 9,073 |
| PCS6-C | 8737 | 8737 | 13233 | 3.446 | 2.061 | 0.021 | 0.413 | 1.968 | 198.50 | 1.6563 | 7.2188 | 347.49 | 129.54 | 32% | 6,617 |
| Average | 8679 | 8679 | 16653 | 4.34 | 2.88 | 0.32 | 0.38 | 2.75 | 249.8 | 1.604 | 7.208 | 347.49 | 129.54 | 55% | 8327 |
| PCS7-A | 8820 | 8820 | 18661 | 4.860 | 7.434 | 0.847 | 0.809 | 7.063 | 279.91 | 1.2813 | 7.1563 | 368.3 | 54.93 | 72% | 9,330 |
| PCS7-B | 8820 | 8820 | 19484 | 5.074 | 6.744 | 0.615 | 0.905 | 6.413 | 292.26 | 1.5313 | 6.9375 | 368.3 | 54.93 | 76% | 9,742 |
| PCS7-C | 8926 | 8926 | 15561 | 4.0524 | 4.4584 | 0.2757 | 0.7599 | 4.2497 | 233.42 | 1.5938 | 7.2813 | 368.3 | 54.93 | 57% | 7,781 |
| Average | 8855 | 8855 | 17902 | 4.66 | 6.21 | 0.58 | 0.82 | 5.91 | 268.5 | 1.469 | 7.125 | 368.3 | 54.93 | 68% | 8951 |
| PCS8-A | 8864 | 8864 | 15051 | 3.9195 | 4.3814 | 0.6930 | 0.3873 | 4.1765 | 225.76 | 1.2500 | 7.1875 | 347.49 | 129.54 | 44% | 7,525 |
| PCS8-B | 8802 | 8802 | 14369 | 3.7420 | 2.6614 | 0.5794 | 0.2102 | 2.5398 | 215.54 | 1.2188 | 7.1875 | 347.49 | 129.54 | 39% | 7,185 |
| PCS8-C | 8802 | 8802 | 16901 | 4.4013 | 5.2511 | 0.6607 | 0.5929 | 5.0017 | 253.51 | 1.2813 | 7.1563 | 347.49 | 129.54 | 57% | 8,450 |
| Average | 8823 | 8823 | 15440 | 4.02 | 4.10 | 0.64 | 0.40 | 3.91 | 231.6 | 1.250 | 7.177 | 347.49 | 129.54 | 47% | 7720 |
| PCS9-A | 8564 | 8564 | 21311 | 5.550 | 1.809 | 0.190 | 0.180 | 1.727 | 319.67 | 1.5625 | 7.3438 | 347.49 | 129.54 | 87% | 10,656 |
| PCS9-B | 8650 | 8650 | 20804 | 5.418 | 1.882 | 0.235 | 0.133 | 1.797 | 312.06 | 1.6250 | 7.3125 | 347.49 | 129.54 | 84% | 10,402 |
| PCS9-C | 8650 | 8650 | 22455 | 5.848 | 2.573 | 0.152 | 0.356 | 2.456 | 336.82 | 1.5625 | 7.4375 | 347.49 | 129.54 | 95% | 11,227 |
| Average | 8621 | 8621 | 21524 | 5.61 | 2.09 | 0.19 | 0.22 | 1.99 | 322.9 | 1.583 | 7.365 | 347.49 | 129.54 | 89% | 10762 |
| Tin1-A | 8214 | 8214 | 21867 | 5.69 | 0.47 | NA | NA | 0.446 | 328.0 | NA | NA | | | | |
| Tin1-B | 8275 | 8275 | 20331 | 5.29 | 0.58 | NA | NA | 0.553 | 305.0 | NA | NA | | | | |
| Tin1-C | 8627 | 8627 | 20044 | 5.22 | 0.71 | NA | NA | 0.681 | 300.7 | 1.438 | 8.375 | | | | |
| Average | 8451 | 8451 | 20747 | 5.40 | 0.59 | NA | NA | 0.56 | 311.2 | | | | | | |
| Tin2-A | 8199 | 8199 | 21847 | 5.69 | 0.84 | NA | NA | 0.802 | 327.7 | NA | NA | | | | |
| Tin2-B | 8306 | 8306 | 18635 | 4.85 | 2.89 | NA | NA | 2.758 | 279.5 | NA | NA | | | | |
| Tin2-C | 8627 | 8627 | 18987 | 4.94 | 4.35 | NA | NA | 4.157 | 284.8 | 1.250 | 8.266 | | | | |
| Average | 8466 | 8466 | 19823 | 5.16 | 2.69 | NA | NA! | 2.57 | 297.3 | | | | | | |



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### 6.1. TS1 6-2-3 Specimen Performance

TS1 consists of a non-composite 6-2-3 tilt-up CSW panel fabricated with THERMOMASS® non-composite shear ties. The panel is non-PS with #3 transverse reinforcement in the structural wythe and WWR in the non-structural wythe. The panel cross-section is illustrated in Figure 38.

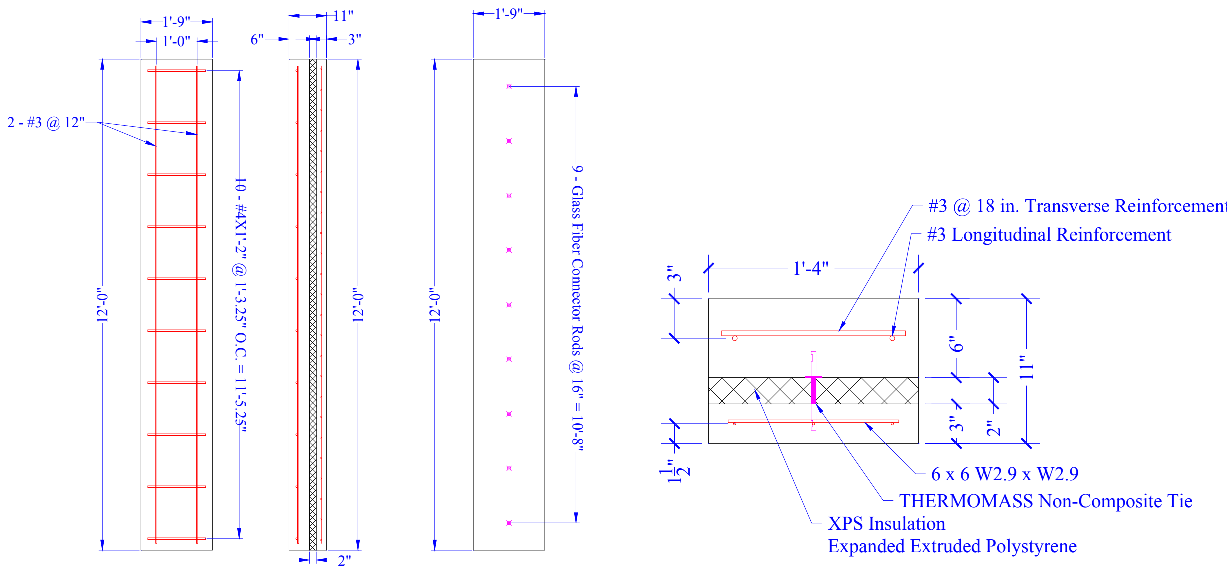


**Figure 38. TS1 Reinforcement Details**

The material properties for the specimen and the measured response are summarized in Table 14 and Table 15. The midspan pressure displacement and moment–support rotation for the three specimens follow in Figures 39 and 40. The individual response of each panel and the quarter point displacements are included at the end in Figures 41-43. Figure 44 shows a picture representation of the three samples post-test.

**Table 14. TS1 Material Properties**

| Property | Value [psi] |
|---|---|
| $f'_c$ Structural Wythe | 4650 |
| $f'_c$ Non-Structural Wythe | 5110 |
| Rebar Yield Strength | 69710 |
| Rebar Ultimate Strength | 107118 |
| WWR Yield Strength | 93930 |
| WWR Ultimate Strength | 96620 |


Distribution Statement A: Approved for public release; distribution unlimited.

**Table 15. TSI Measured Response**

| Specimen | Type | Max Load [lbs] | Max Pressure [psi] | Corresponding Displacement [in] | Corr. Rotation [deg] | Measured Moment Capacity [k-in] |
|---|---|---|---|---|---|---|
| TS1-A | 6-2-3 | 6508 | 3.389 | 5.32 | 5.07 | 97.61 |
| TS1-B | 6-2-3 | 4918 | 2.561 | 6.21 | 5.91 | 73.77 |
| TS1-C | 6-2-3 | 6450 | 3.359 | 3.61 | 3.45 | 96.75 |
| | Average | 5958 | 3.1 | 5.0 | 4.8 | 89.4 |
| | COV | 15.1% | 15.1% | 26.2% | 26.1% | 15.1% |

**Figure 39. TS1 6-2-3 Pressure—Midspan Displacement**

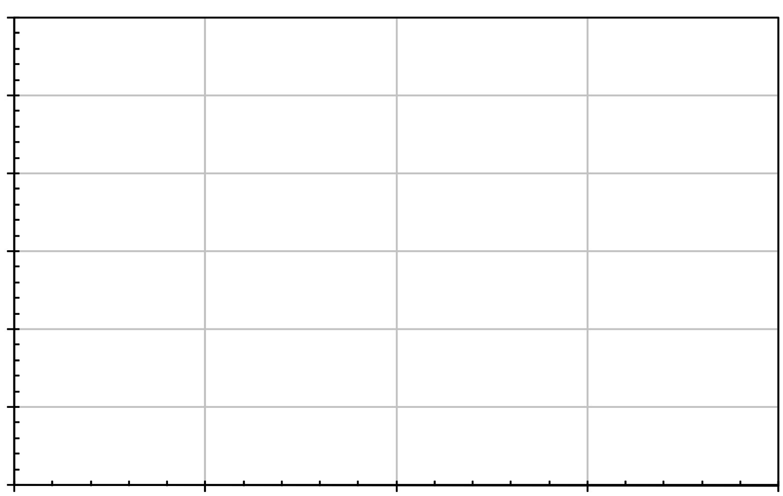

**Figure 40. TS1 6-2-3 Moment—Rotation**



Distribution Statement A: Approved for public release; distribution unlimited.

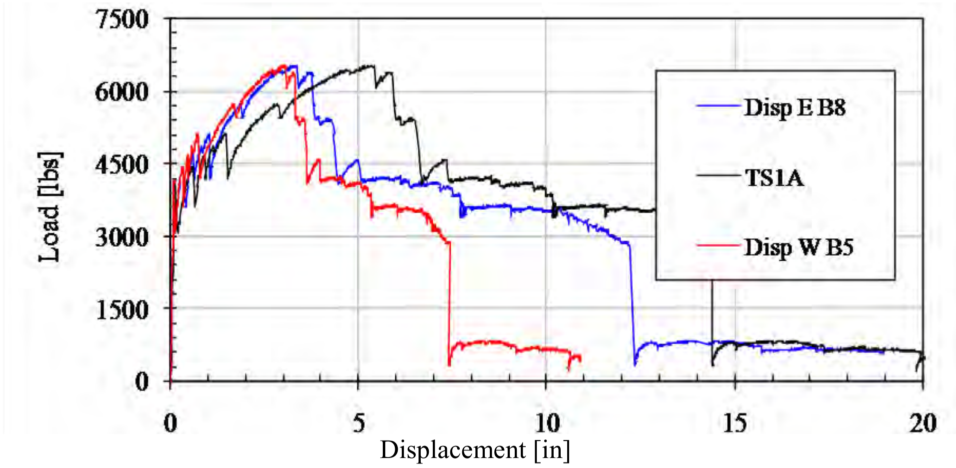


**Figure 41. TS1-A Detail Results**

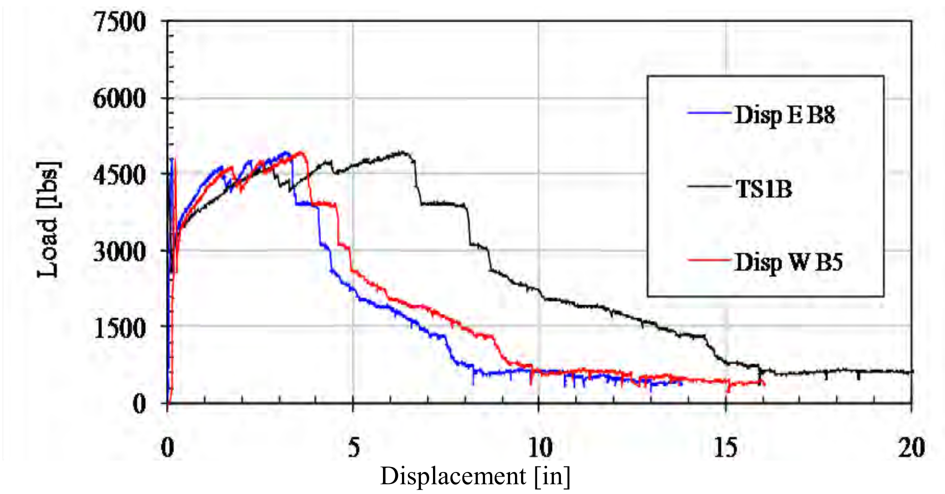


**Figure 42. TS1-B Detail Results**

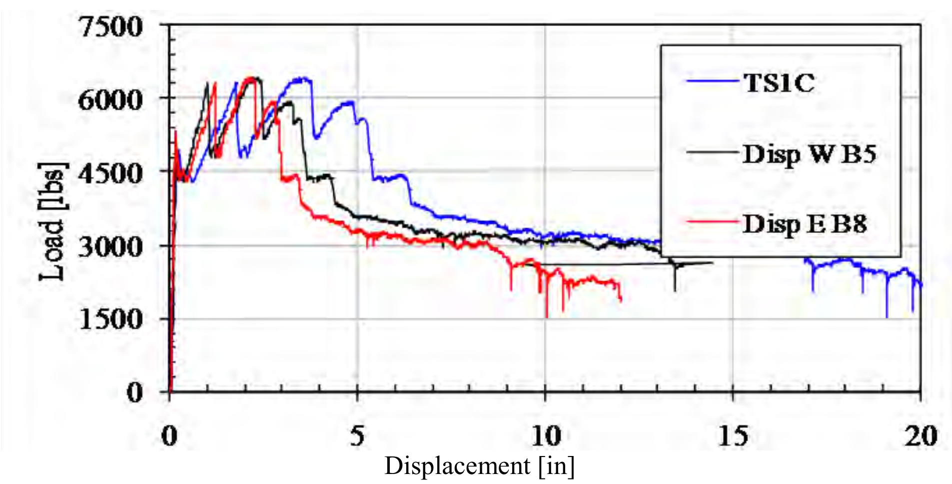


**Figure 43. TS1-C Detail Results**



Distribution Statement A: Approved for public release; distribution unlimited.

**Figure 44. TS1 Panel Response (A, B, C)**

### 6.2. TS2 3-2-3 Specimen Performance

TS2 consists of a partially composite 3-2-3 tilt-up CSW panel fabricated with THERMOMASS® composite shear ties. The panel is non-PS with #3 transverse reinforcement in the structural wythe and WWR in both the interior and exterior wythe. The panel cross-section is illustrated in Figure 45.

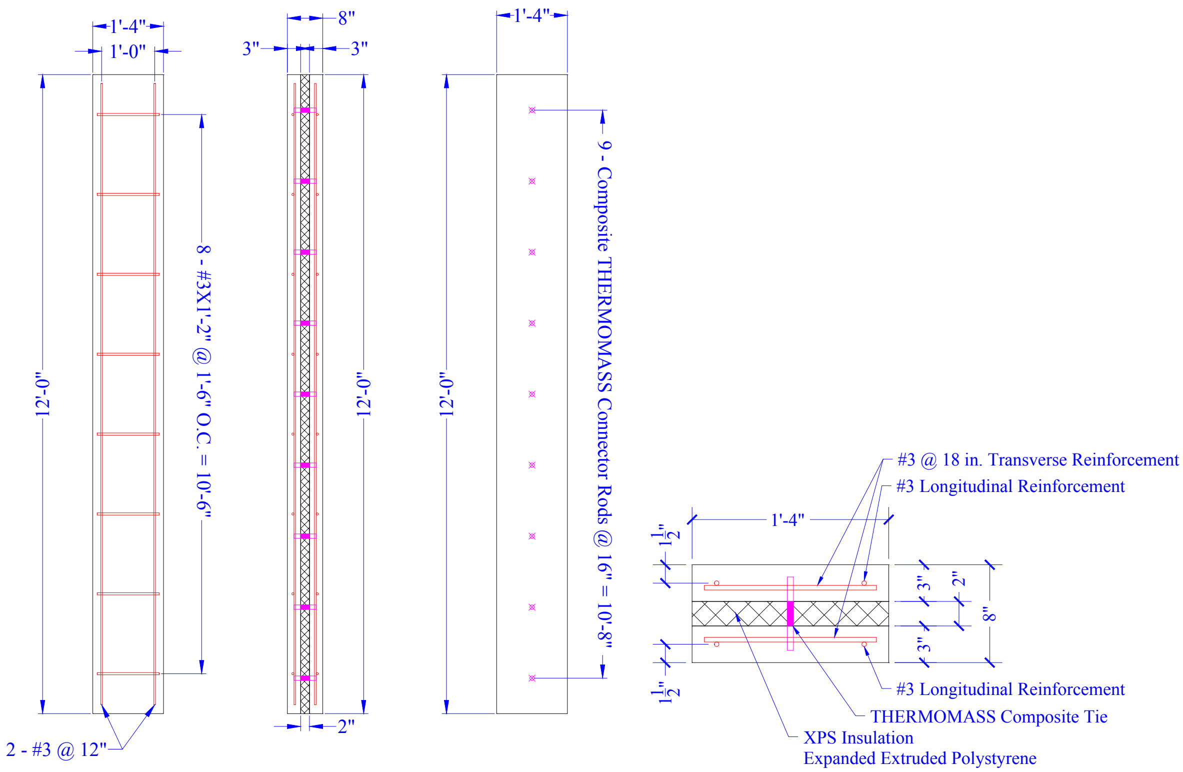


**Figure 45. TS2 Reinforcement Details**

The material properties for the specimen and the measured response are summarized in Tables 16 and 17. The midspan pressure displacement and moment–support rotation for the three specimen follow in Figures 46 and 47. The individual response of each panel and the quarter point displacements are included at the end in Figures 48-50. Figure 51 shows a picture representation of the three samples post-test.


Distribution Statement A: Approved for public release; distribution unlimited.

**Table 16. TS2 Material Properties**

| Property | Value [psi] |
|---|---|
| $f'_c$ Structural Wythe | 4650 |
| $f'_c$ Non-Structural Wythe | 5110 |
| Rebar Yield Strength | 69710 |
| Rebar Ultimate Strength | 107118 |
| WWR Yield Strength | 93930 |
| WWR Ultimate Strength | 96620 |

**Table 17. TS2 Measured Response**

| Specimen | Type | Max Load [lbs] | Max Pressure [psi] | Corresponding Displacement [in] | Corr. Rotation [deg] | Measured Moment Capacity [k-in] |
|---|---|---|---|---|---|---|
| TS2-A | 3-2-3 | 8020 | 4.177 | 4.92 | 4.69 | 120.30 |
| TS2-B | 3-2-3 | 8210 | 4.276 | 5.05 | 4.81 | 123.15 |
| TS2-C | 3-2-3 | 8020 | 4.177 | 5.92 | 5.63 | 120.30 |
| | Average | 8083 | 4.2 | 5.3 | 5.0 | 121.3 |
| | COV | 1.4% | 1.4% | 10.2% | 10.2% | 1.4% |

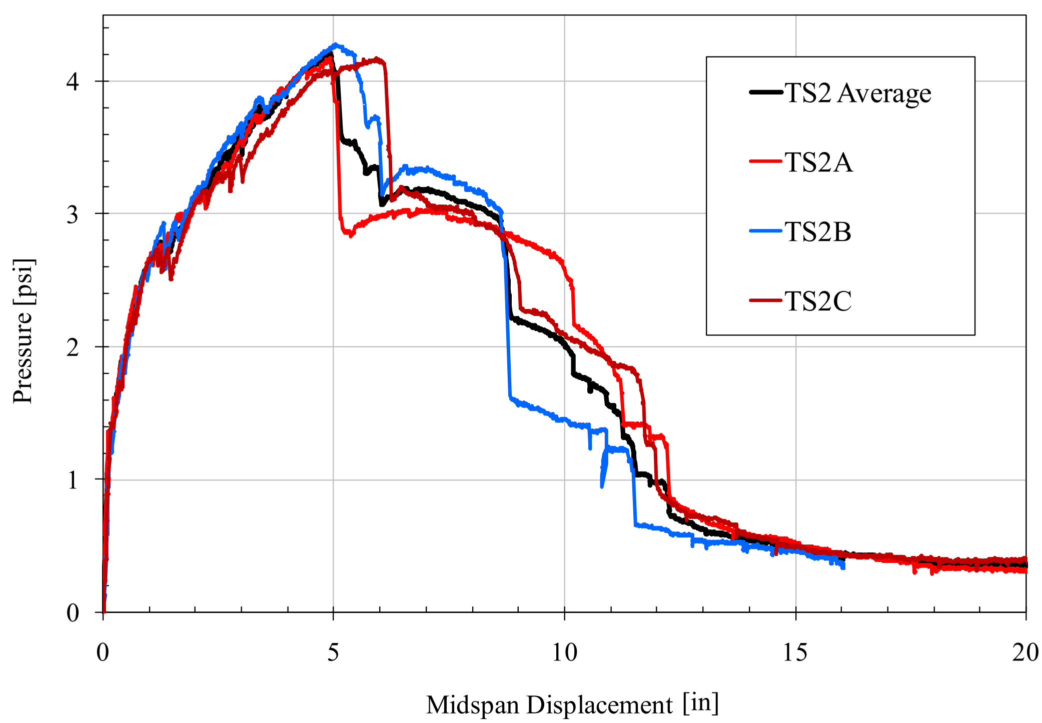


**Figure 46. 3-2-3 Pressure—Midspan Displacement**


Distribution Statement A: Approved for public release; distribution unlimited.

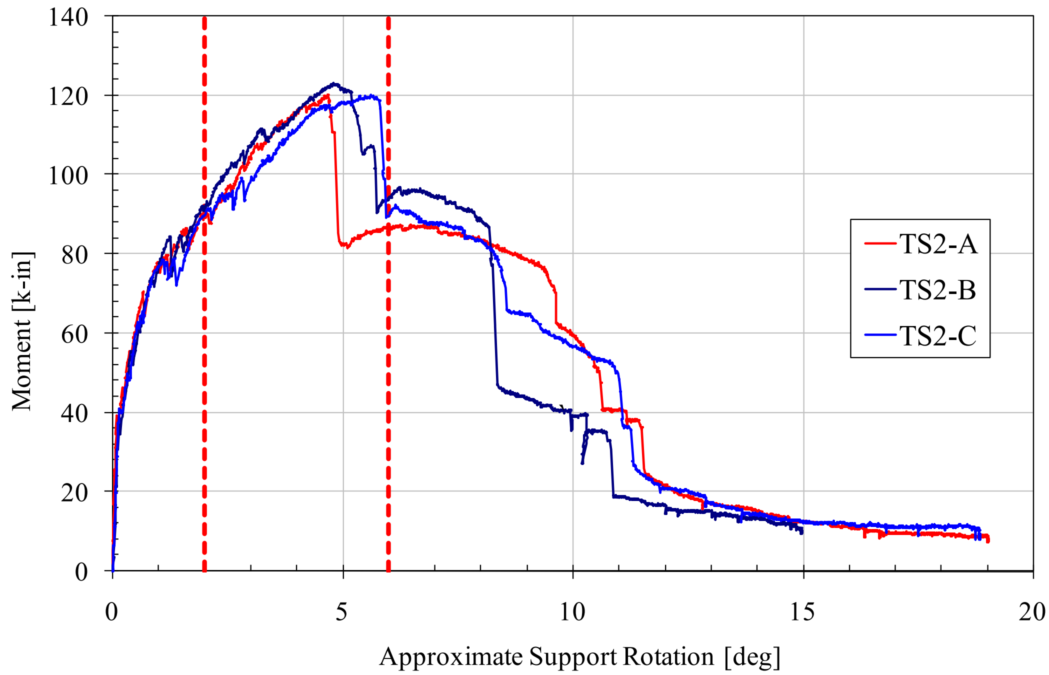


**Figure 47. TS2 3-2-3 Moment Rotation at Midspan**

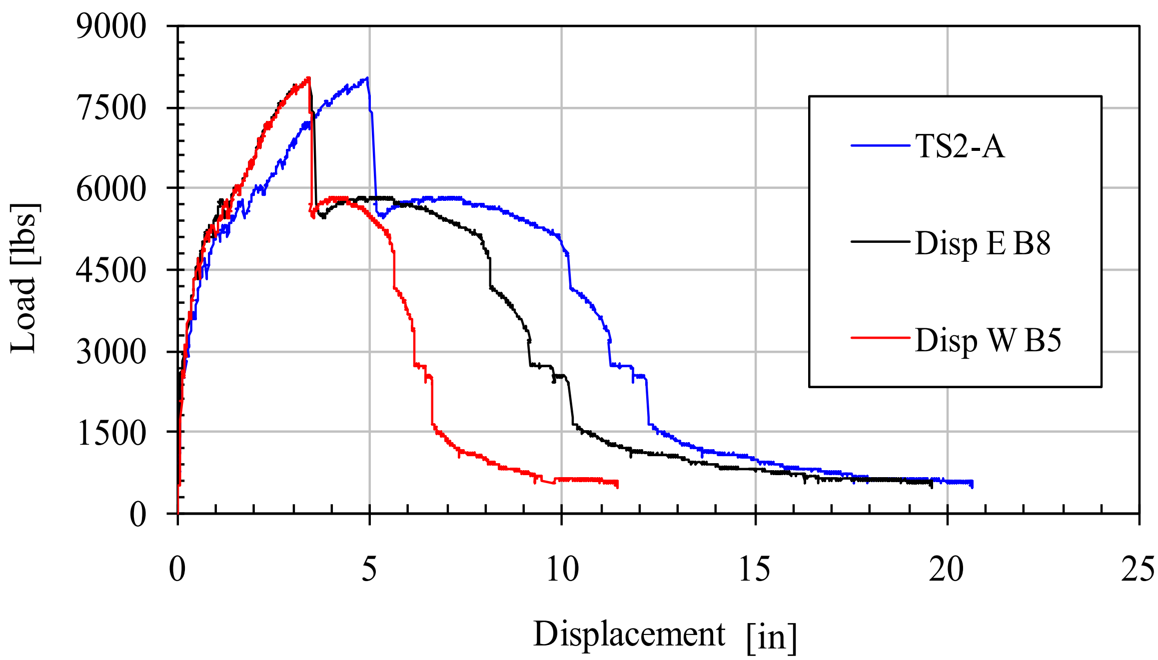


**Figure 48. TS2-A Detail Results**



Distribution Statement A: Approved for public release; distribution unlimited.

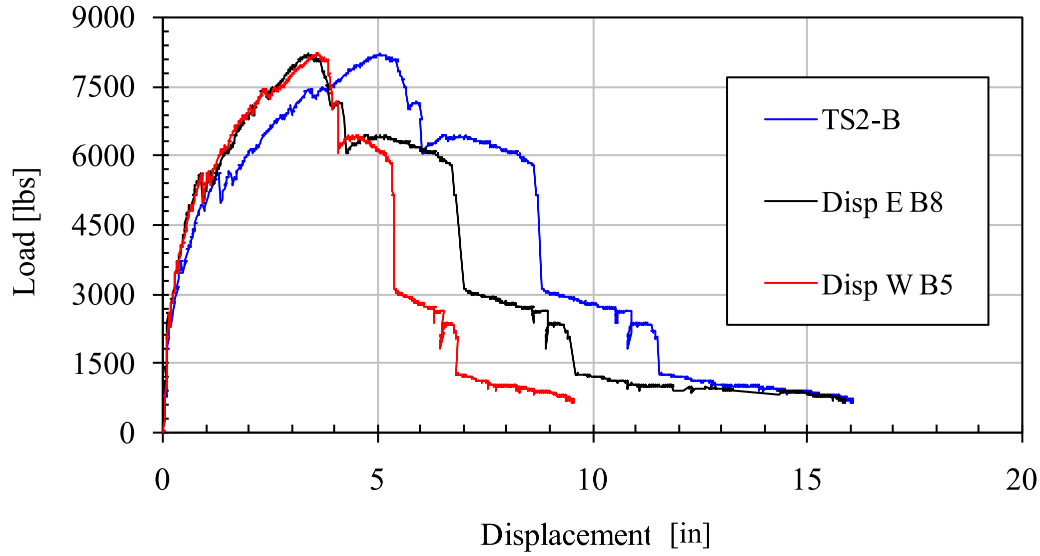


**Figure 49. TS2-B Detail Results**

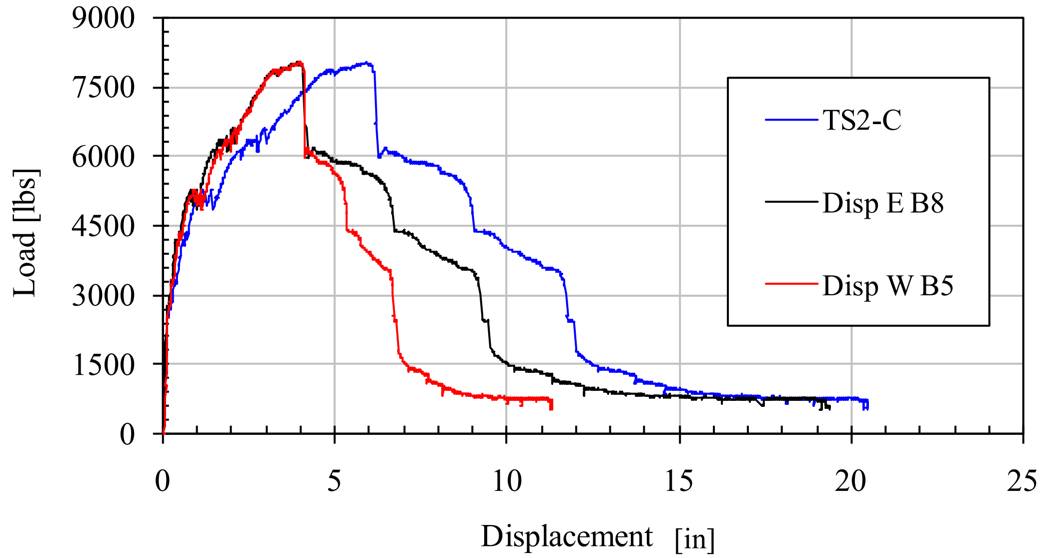


**Figure 50. TS2-C Detail Results**

**Figure 51. TS2 Panel Response (A, B, C)**


Distribution Statement A: Approved for public release; distribution unlimited.

## 6.3. PCS1 3-2-3 Specimen Performance

PCS1 consists of a partially composite 3-2-3 PC CSW panel fabricated with EPS insulation and steel C-clip shear ties. The panel is PS with WWR transverse reinforcement in both the interior and exterior wythe. The panel cross-section is illustrated in Figures 52 and 53.

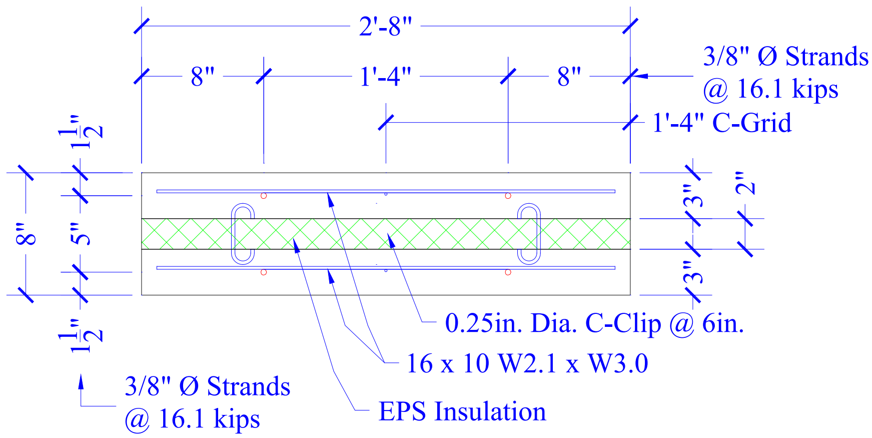


**Figure 52. PCS1 Cross-Section Detail**

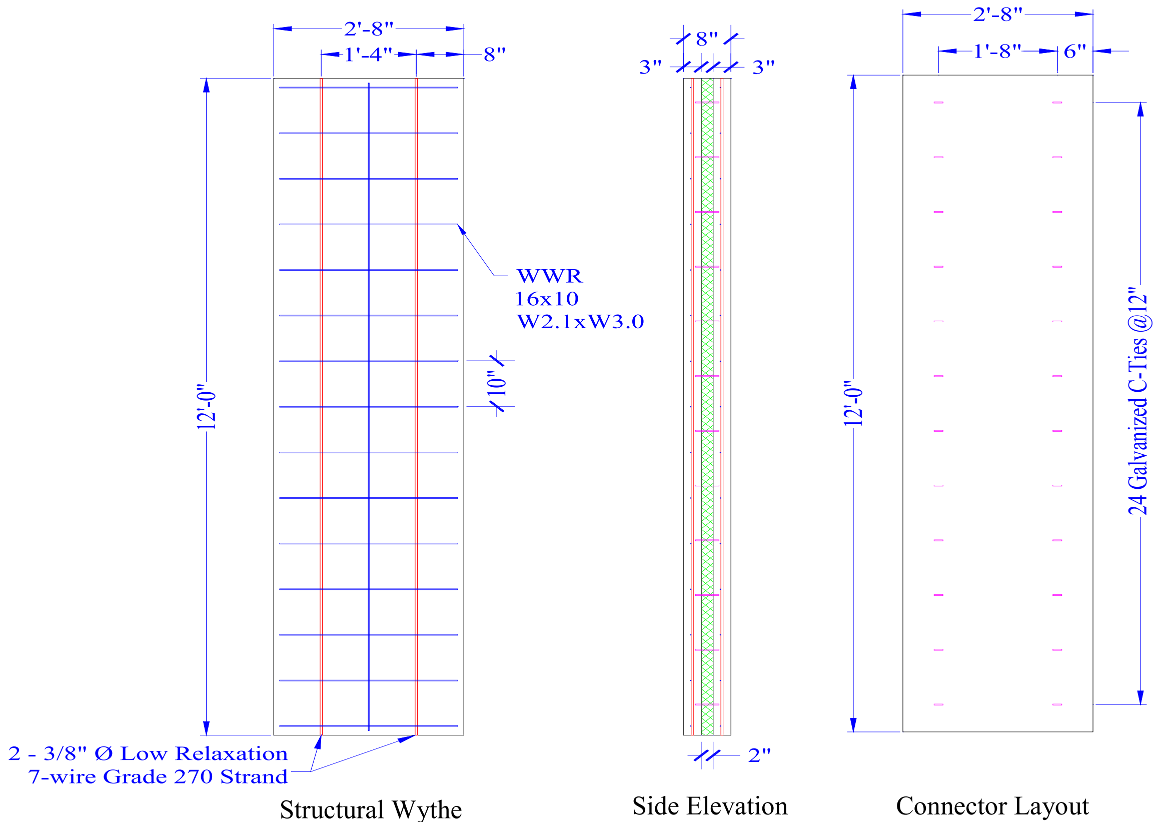


**Figure 53. PCS1 Panel Detail**



Distribution Statement A: Approved for public release; distribution unlimited.

The measured response is summarized in the Table 18. The midspan pressure displacement and moment-support rotation for the three specimen are in Figures 54 and 55. The individual response of each panel and the quarter point displacements are included in Figures 56-58. A picture representation of the samples post-test is shown in Figure 59

**Table 18. PCS1 Measured Response**

| Specimen | Wythe Configuration | Age at Test [days] | Max Load [lbs] | Max Pressure [psi] | Corresponding Displacement [in] | East Slip [in] | West Slip [in] | Measured Moment Capacity [k-in] |
|---|---|---|---|---|---|---|---|---|
| PCS1-A | 3-2-3 | 20 | 17728 | 4.617 | 1.712 | 0.144 | 0.142 | 265.92 |
| PCS1-B | 3-2-3 | 21 | 17693 | 4.608 | 2.010 | 0.134 | 0.187 | 265.39 |
| PCS1-C | 3-2-3 | 22 | 16399 | 4.271 | 1.832 | 0.126 | 0.195 | 245.98 |
| | | Average | 17273 | 4.498 | 1.851 | 0.135 | 0.175 | 259.10 |
| | | COV | 4.4% | 4.4% | 8.1% | 6.7% | 16.1% | 4.4% |

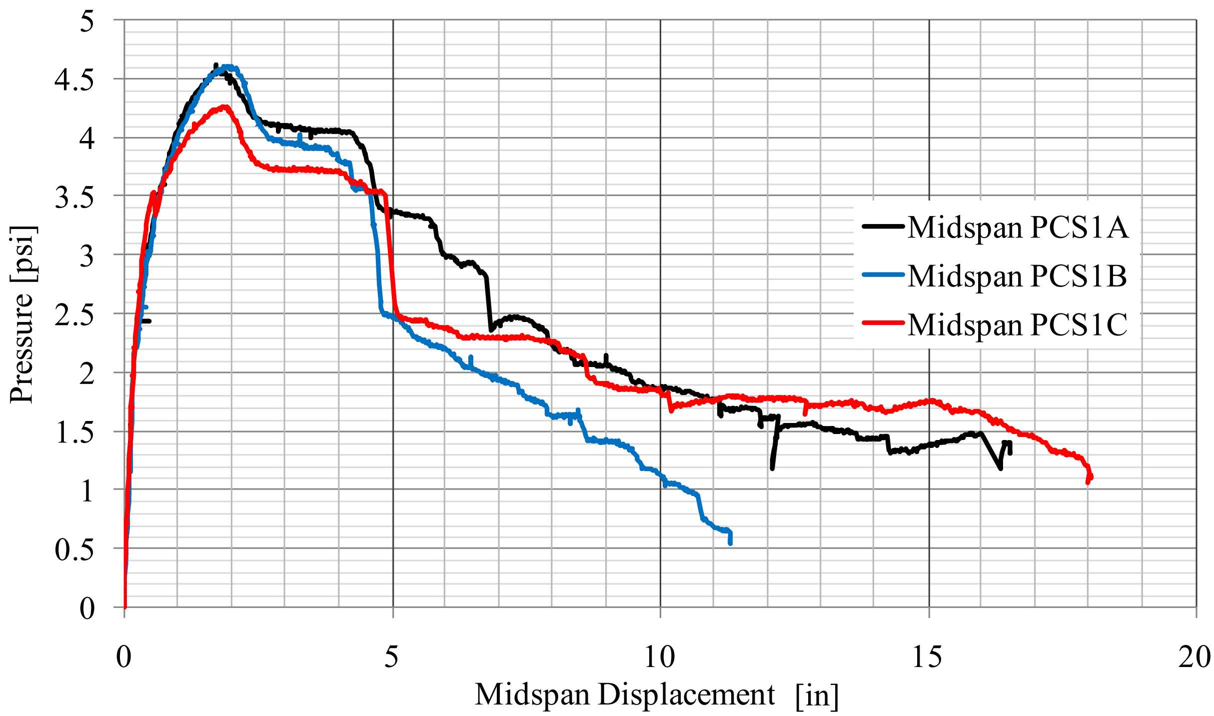


**Figure 54. PCS1 Pressure–Displacement Response**



Distribution Statement A: Approved for public release; distribution unlimited.

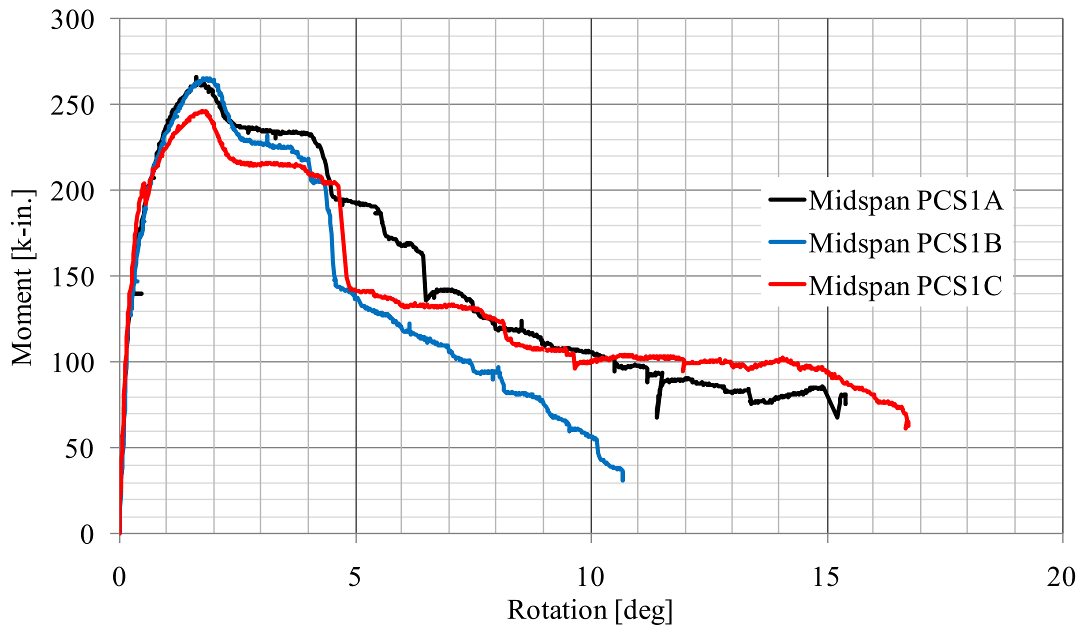


**Figure 55. PCS1 Moment–Rotation Response**

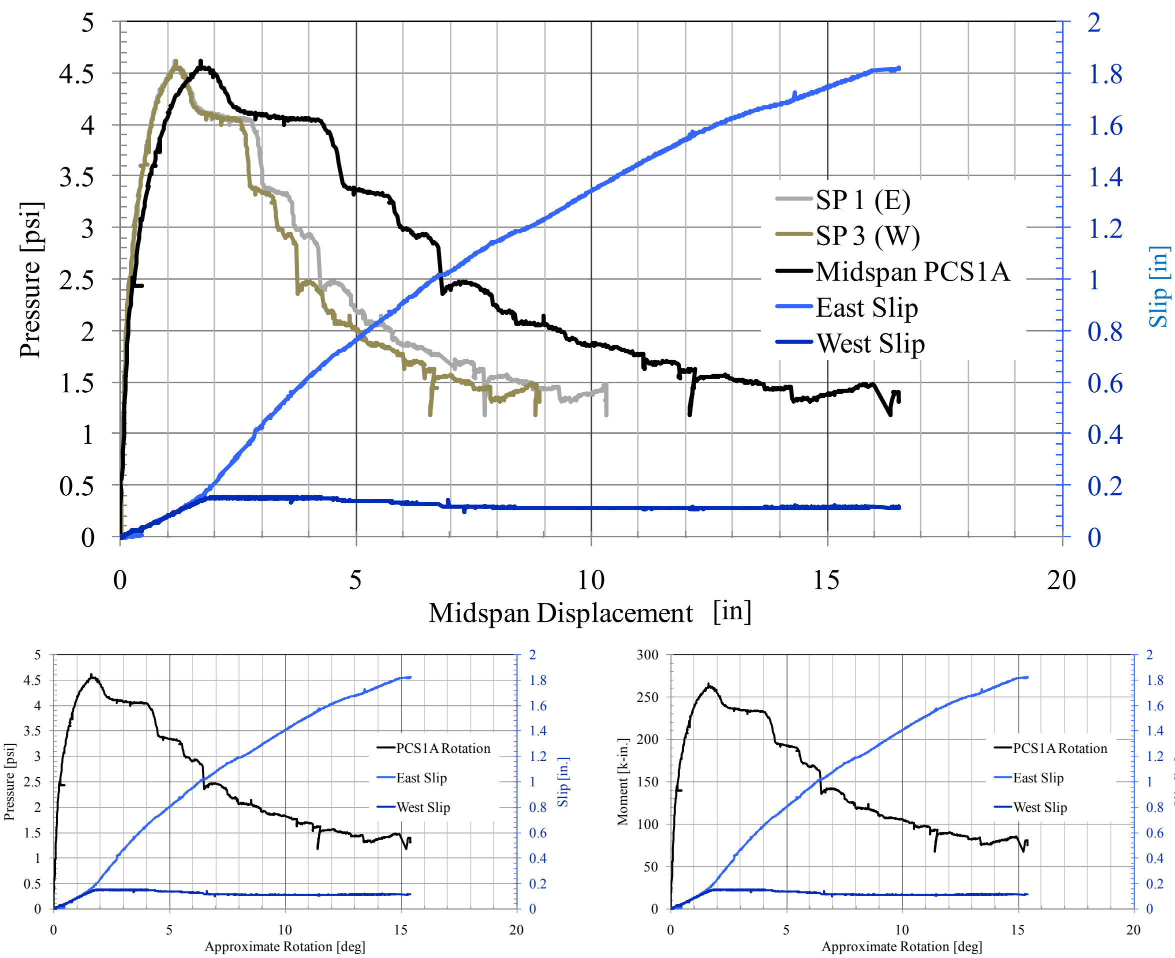


**Figure 56. PCS1-A Response**



Distribution Statement A: Approved for public release; distribution unlimited.

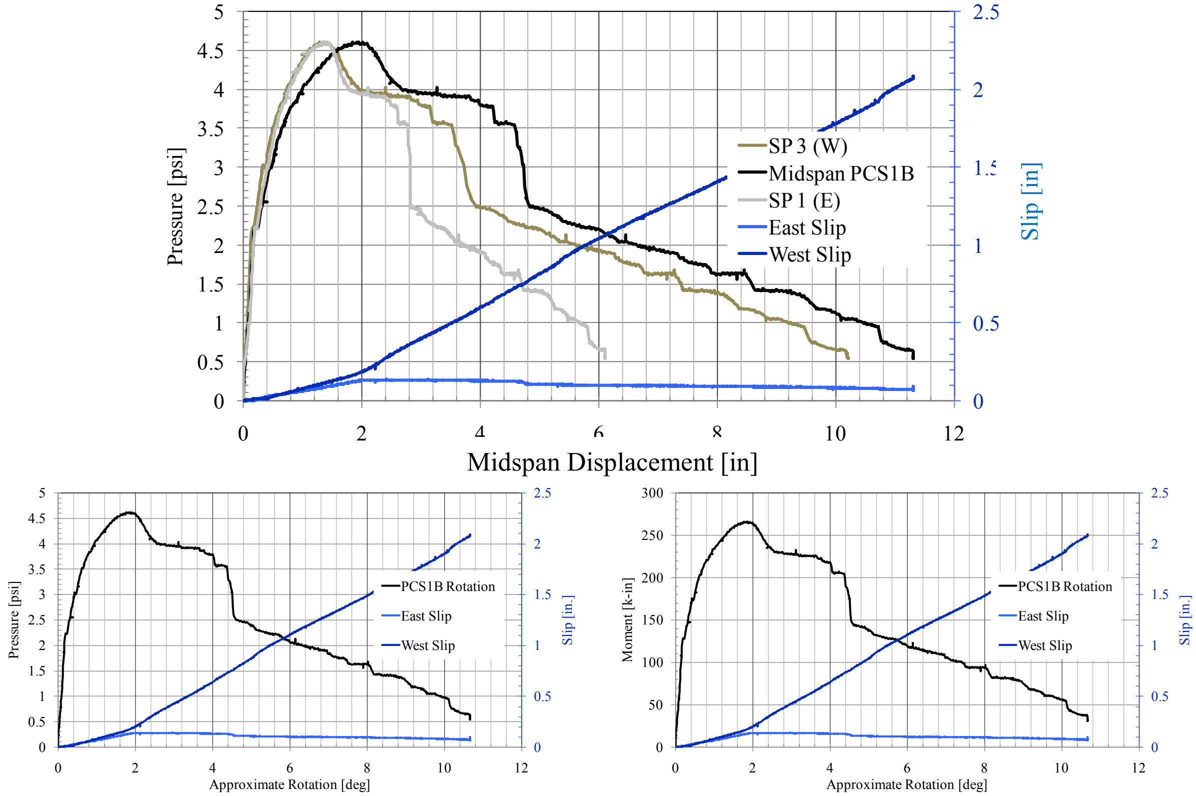


**Figure 57. PCS1-B Response**

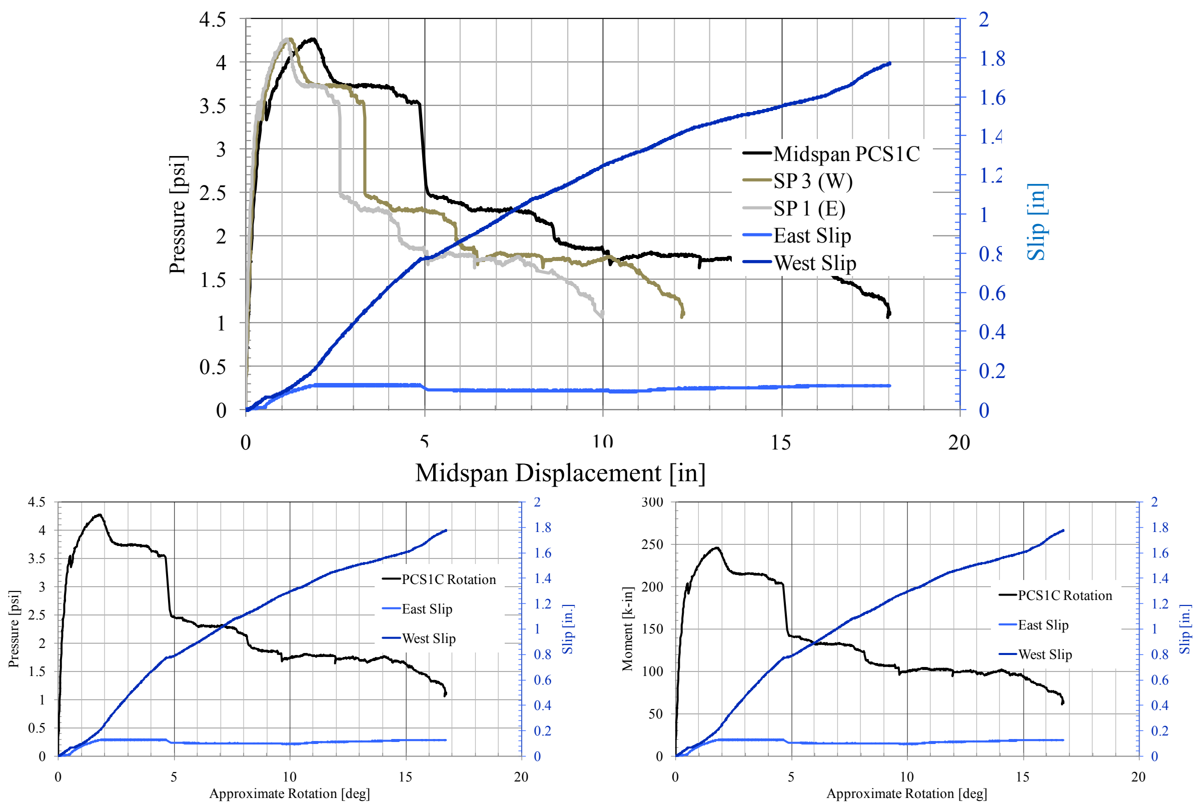


**Figure 58. PCS1-C Response**


Distribution Statement A: Approved for public release; distribution unlimited.

Figure 59. PCS1 Panel Response

### 6.4. PCS2 3-2-3 Specimen Performance

PCS2 consists of a partially composite 3-2-3 PC CSW panel fabricated with C-Grid® carbon fiber reinforced polymer mesh shear ties. The panel is PS and uses WWR transverse reinforcement in both the interior and exterior wythe. Expanded polystyrene is used. This is the standard insulation recommended for C-Grid® panels. The panel cross-section is illustrated in Figures 60 and 61.

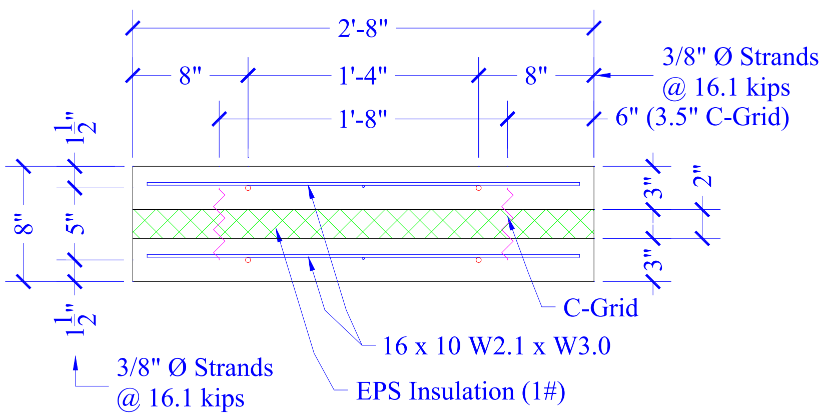


Figure 60. PCS2 Cross-Section Detail

The measured response is summarized in Table 19. The midspan pressure displacement and moment-support rotation for the three specimen are in Figures 62 and 63. The individual response of each panel and the end slip and quarter point displacements are included in Figures 64-66. Figure 67 shows a picture representation of the samples post-test.

Table 19. PCS2 Measured Response

| Specimen | Age at Test [days] | Max Load [lbs] | Max Pressure [psi] | Corresponding Displacement [in] | East Slip [in] | West Slip [in] | Rot. [deg] | Measured Moment Capacity [k-in] |
|---|---|---|---|---|---|---|---|---|
| PCS2-A | 23 | 20448 | 5.325 | 1.990 | 0.291 | 0.000 | 1.900 | 306.73 |
| PCS2-B | 23 | 19183 | 4.996 | 2.309 | 0.374 | 0.003 | 2.204 | 287.74 |
| PCS2-C | 42 | 19319 | 5.031 | 1.345 | 0.208 | 0.005 | 1.284 | 289.79 |
| | Average | 19650 | 5.12 | 1.88 | 0.29 | 0.002 | 1.80 | 294.8 |


Distribution Statement A: Approved for public release; distribution unlimited.

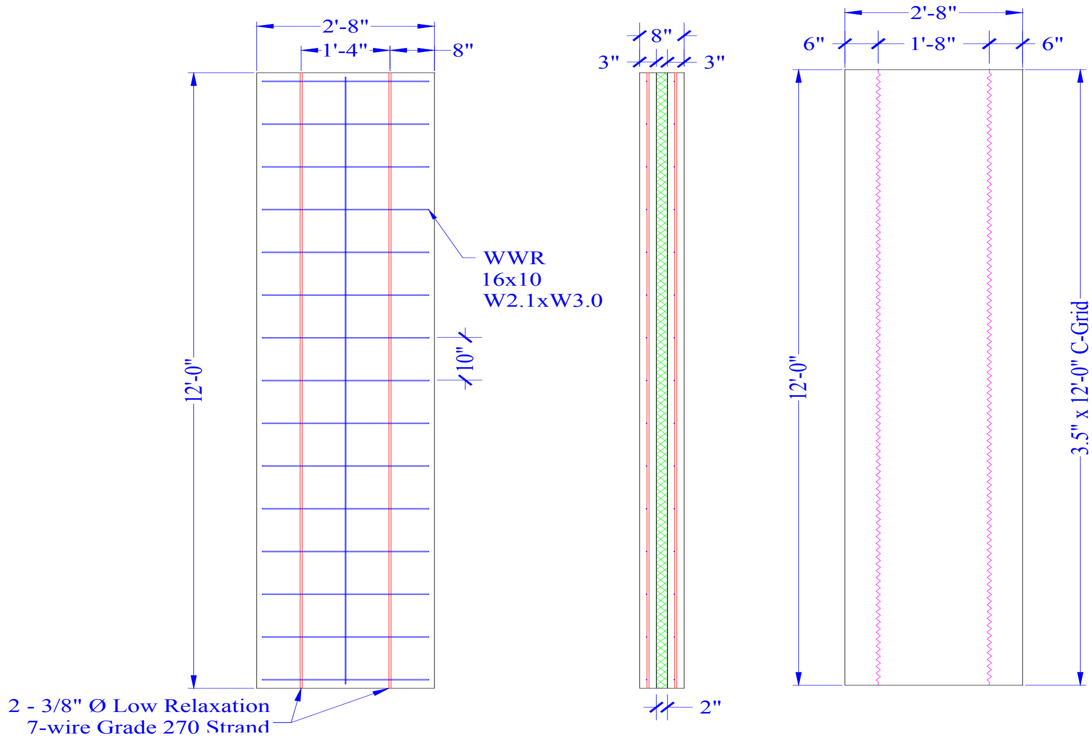


**Figure 61. PCS2 Panel Detail**

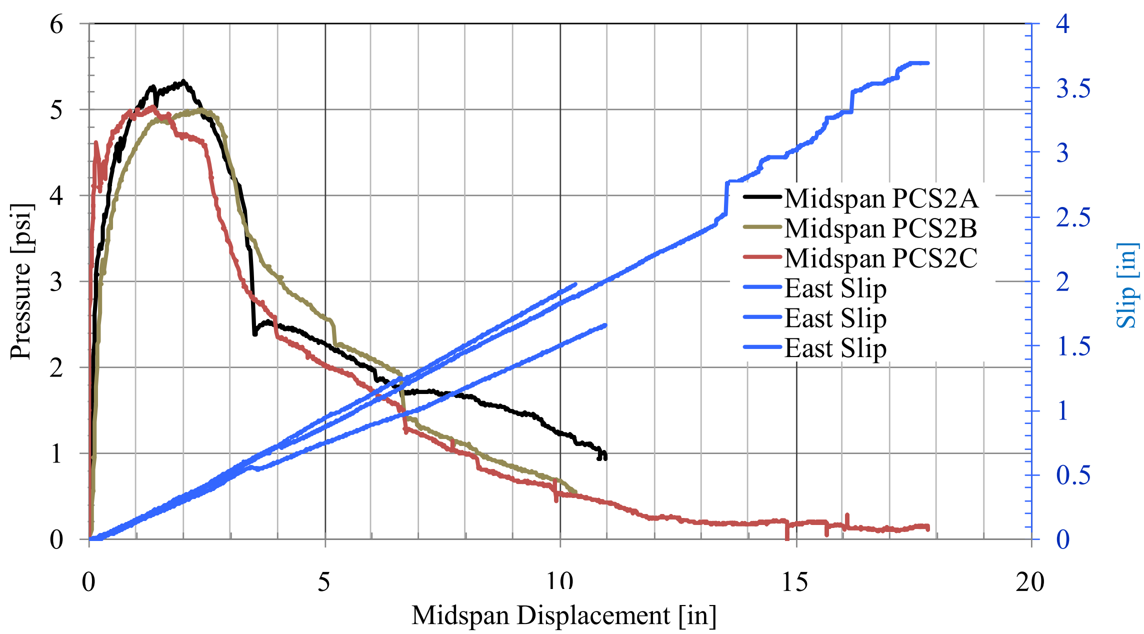


**Figure 62. PCS2 Pressure–Displacement Response**



Distribution Statement A: Approved for public release; distribution unlimited.

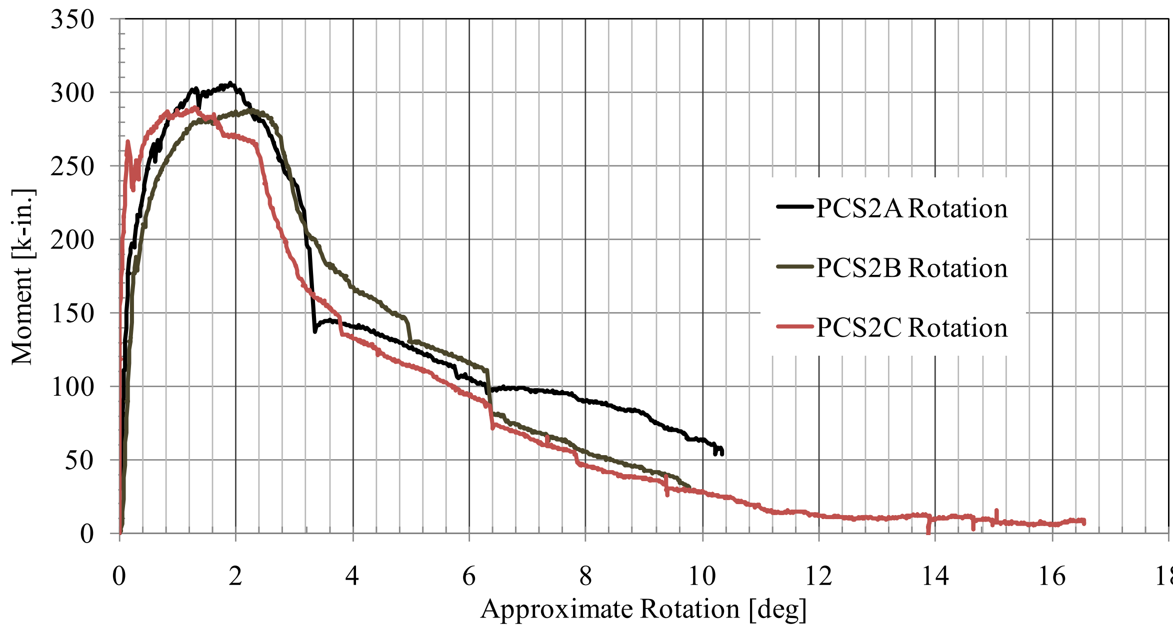


**Figure 63. PCS2 Moment–Rotation Response**

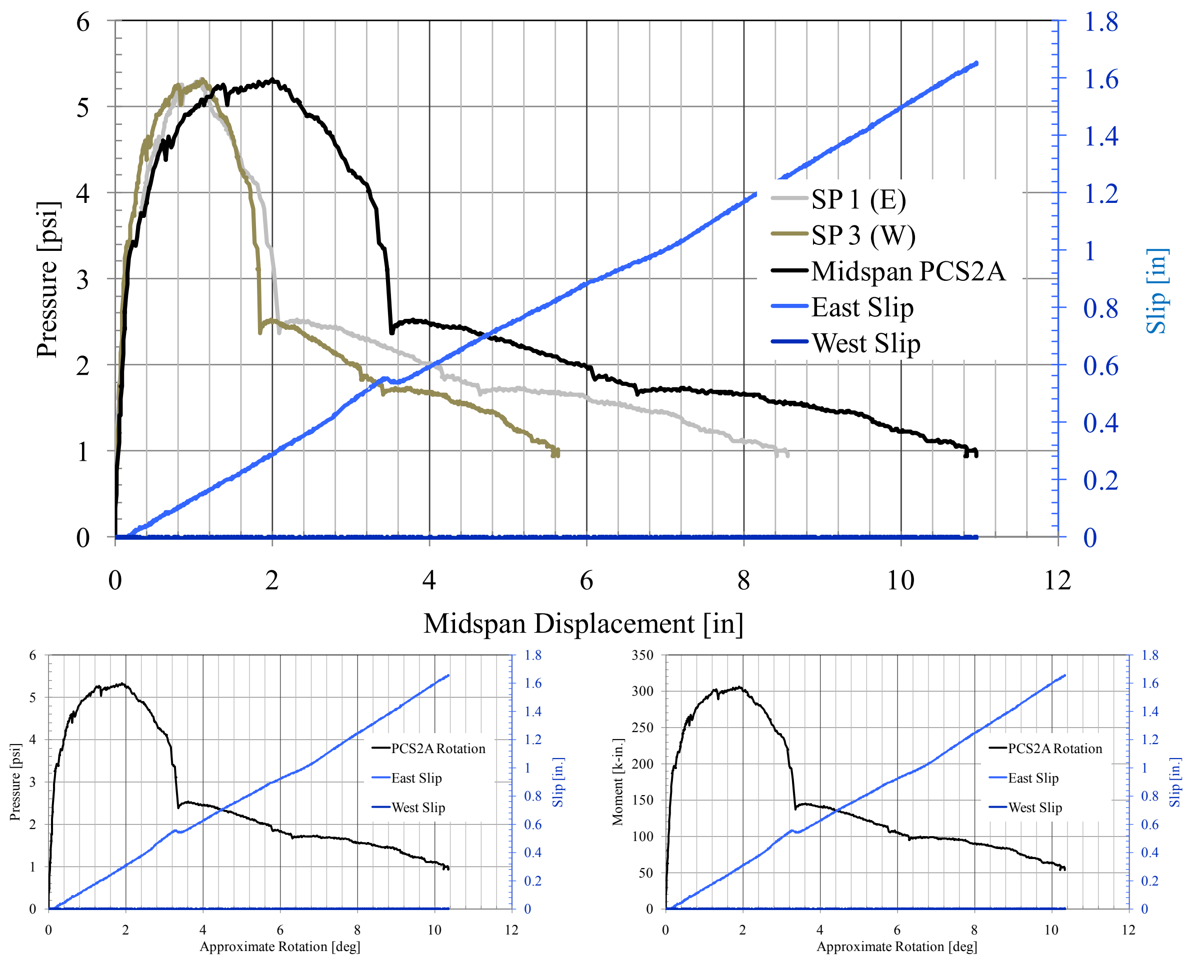


**Figure 64. PCS2-A Response**



Distribution Statement A: Approved for public release; distribution unlimited.

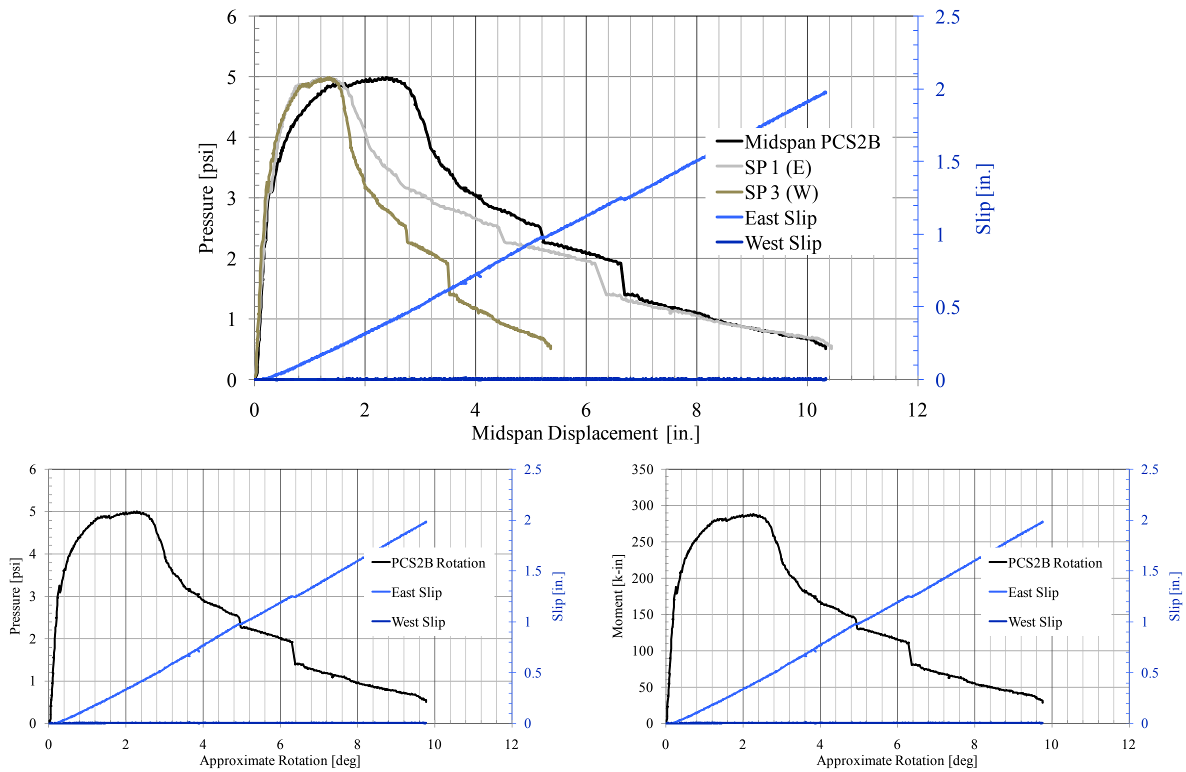


**Figure 65. PCS2-B Pressure–Displacement Response**

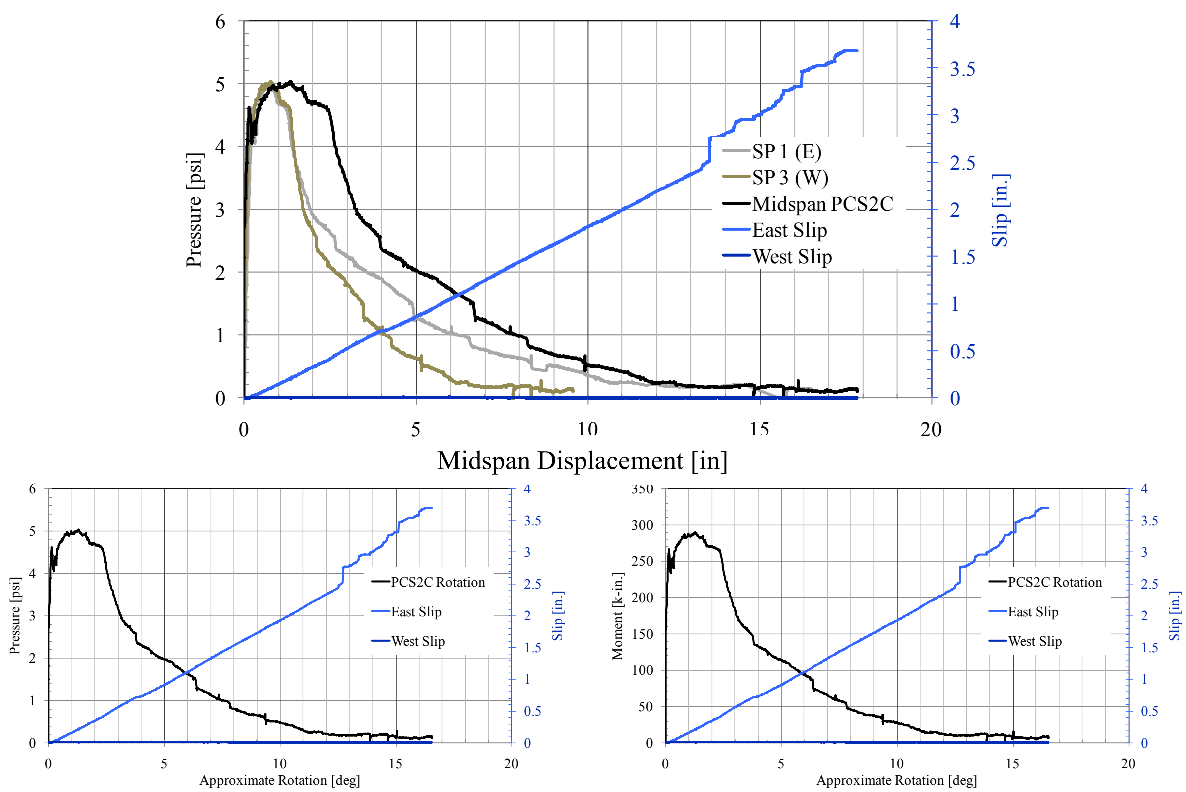


**Figure 66. PCS2-C Response**



Distribution Statement A: Approved for public release; distribution unlimited.

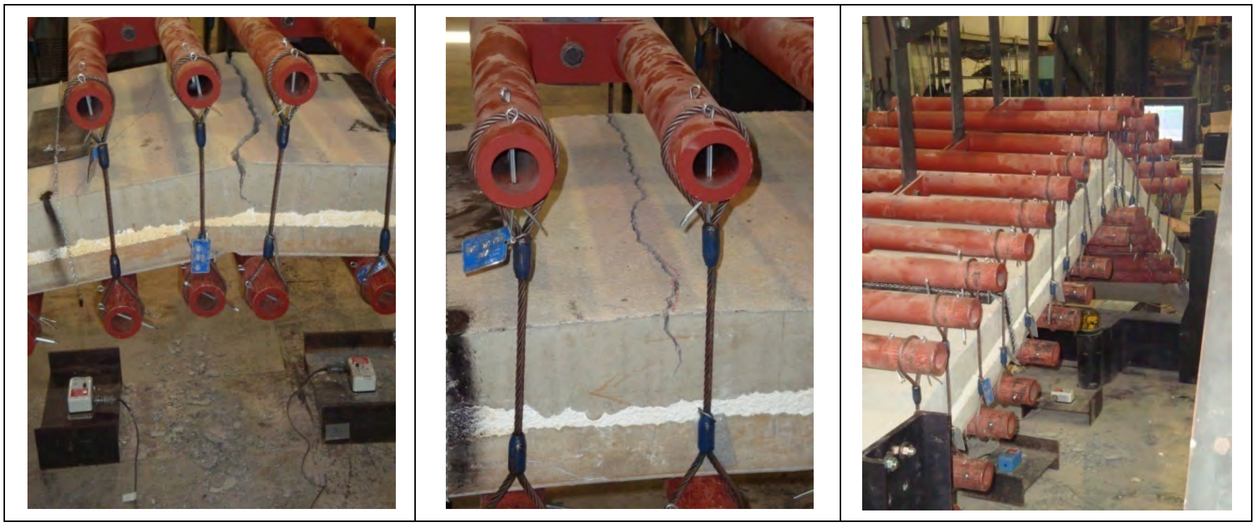

**Figure 67. PCS2 Panel Response (A, B, C)**

### 6.5. PCS3 3-2-3 Specimen Performance

PCS3 consists of a partially composite 3-2-3 PC CSW panel fabricated with EPS insulation and steel C-Grid® carbon fiber shear ties. The panel is non-PS with rebar longitudinal reinforcement and WWR transverse reinforcement in both the interior and exterior wythe. The panel cross-section is illustrated in Figures 68 and 69.

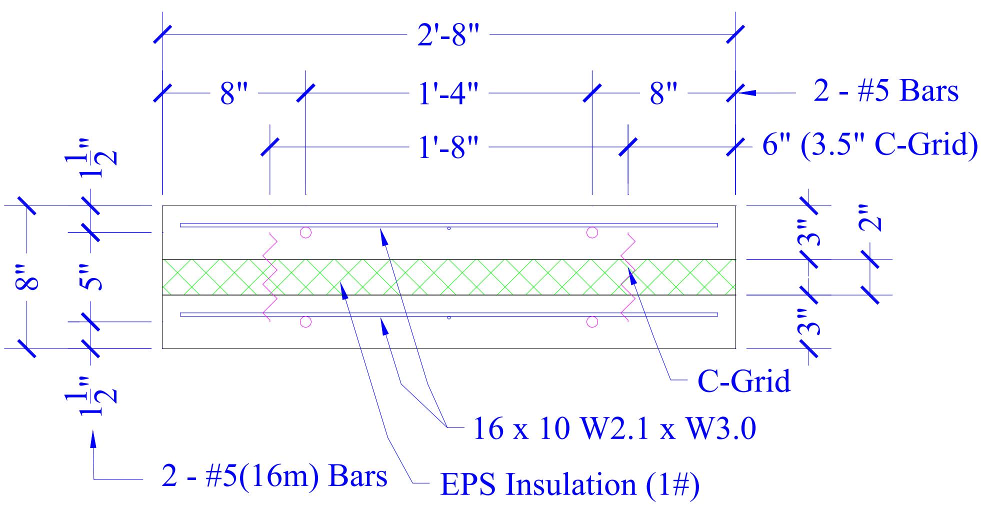


**Figure 68. PCS3 Cross-Section Detail**


Distribution Statement A: Approved for public release; distribution unlimited.

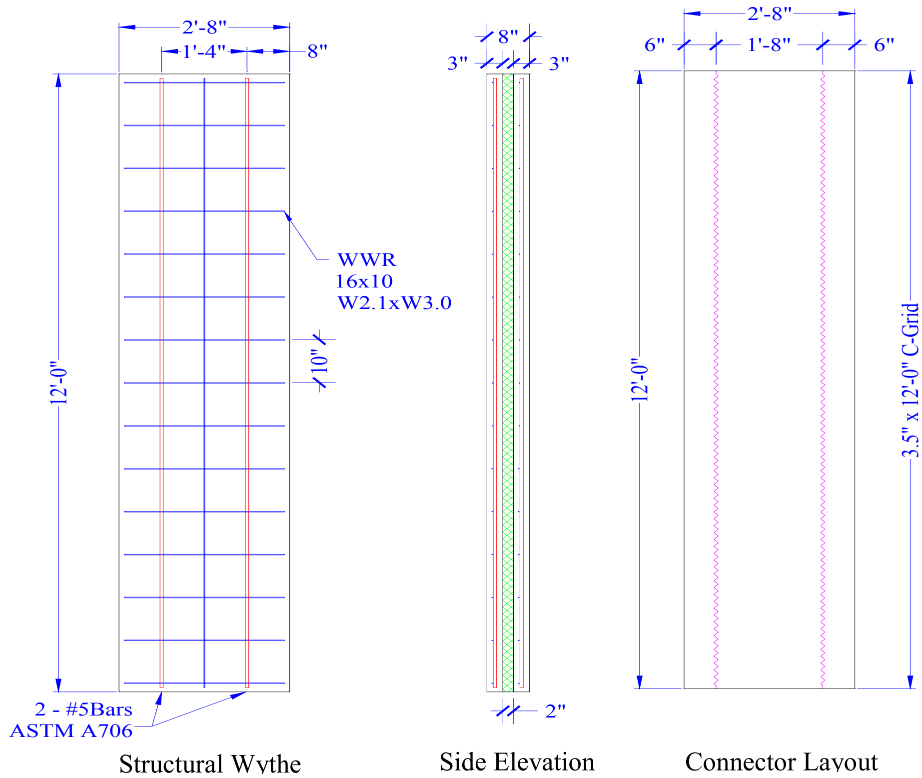


**Figure 69. PCS3 Panel Detail**

The measured response is summarized in Table 20. The midspan pressure displacement and moment-support rotation for the three specimen are in Figures 70 and 71. The individual response of each panel and the end slip and quarter point displacements are included in Figures 72-74. Figure 75 shows a picture representation of the samples post-test.

**Table 20. PCS3 Measured Response**

| Specimen | Age at Test [days] | Max Load [lbs] | Max Pressure [psi] | Corresponding Displacement [in] | East Slip [in] | West Slip [in] | Rot. [deg] | Measured Moment Capacity [k-in] |
|---|---|---|---|---|---|---|---|---|
| PCS3-A | 22 | 21256 | 5.536 | 6.000 | 0.016 | 0.008 | 5.711 | 318.85 |
| PCS3-B | 26 | 16328 | 4.252 | 0.892 | 0.041 | 0.002 | 0.852 | 244.92 |
| PCS3-C | 41 | 23643 | 6.157 | 5.500 | 0.001 | 0.090 | 5.237 | 354.64 |
| | Average | 20409 | 5.31 | 4.13 | 0.02 | 0.03 | 3.93 | 306.1 |


Distribution Statement A: Approved for public release; distribution unlimited.

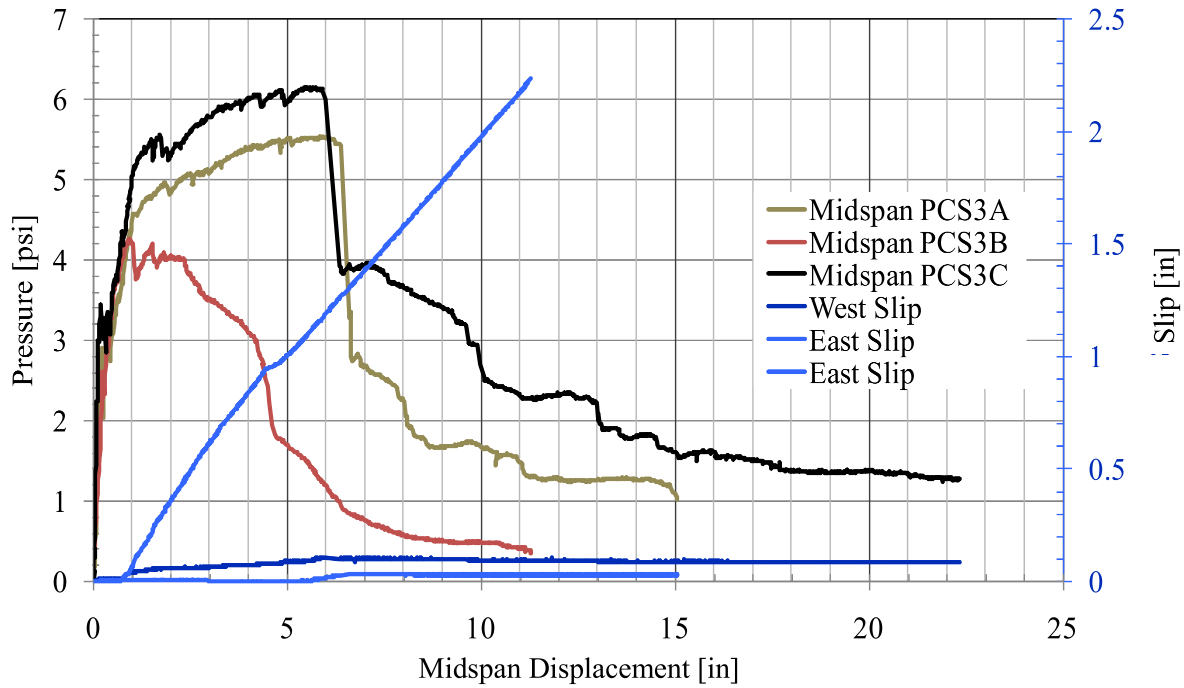


**Figure 70. PCS3 Pressure–Displacement Response**

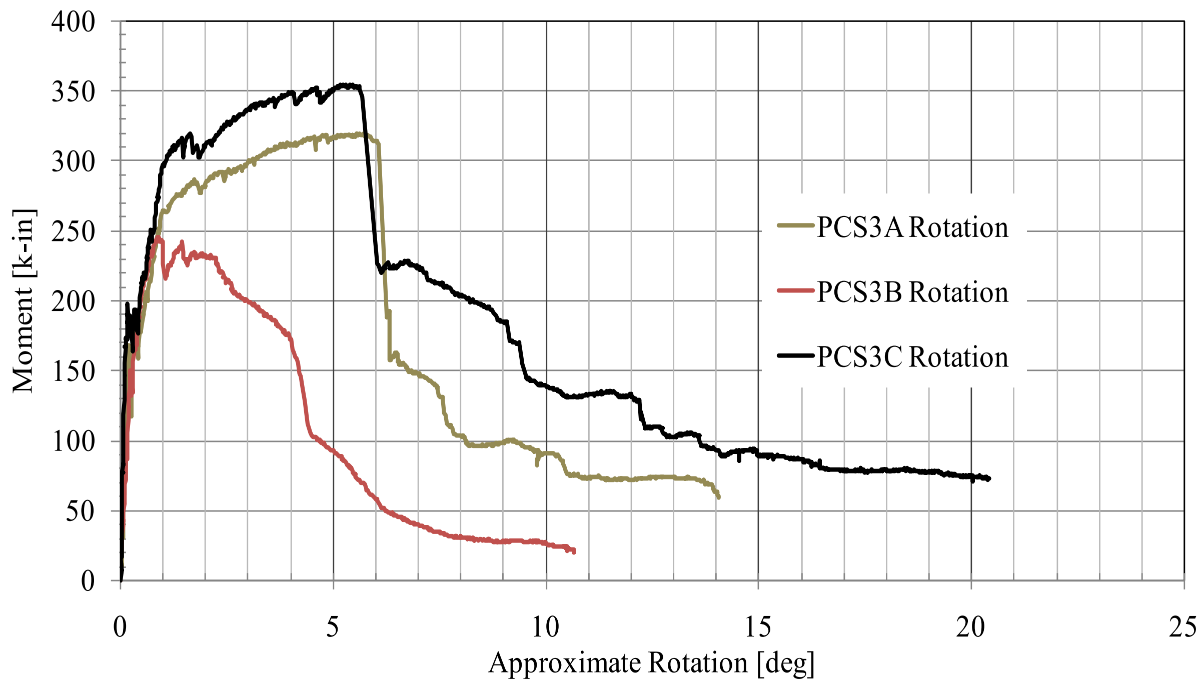


**Figure 71. PCS3 Moment–Rotation Response**


Distribution Statement A: Approved for public release; distribution unlimited.

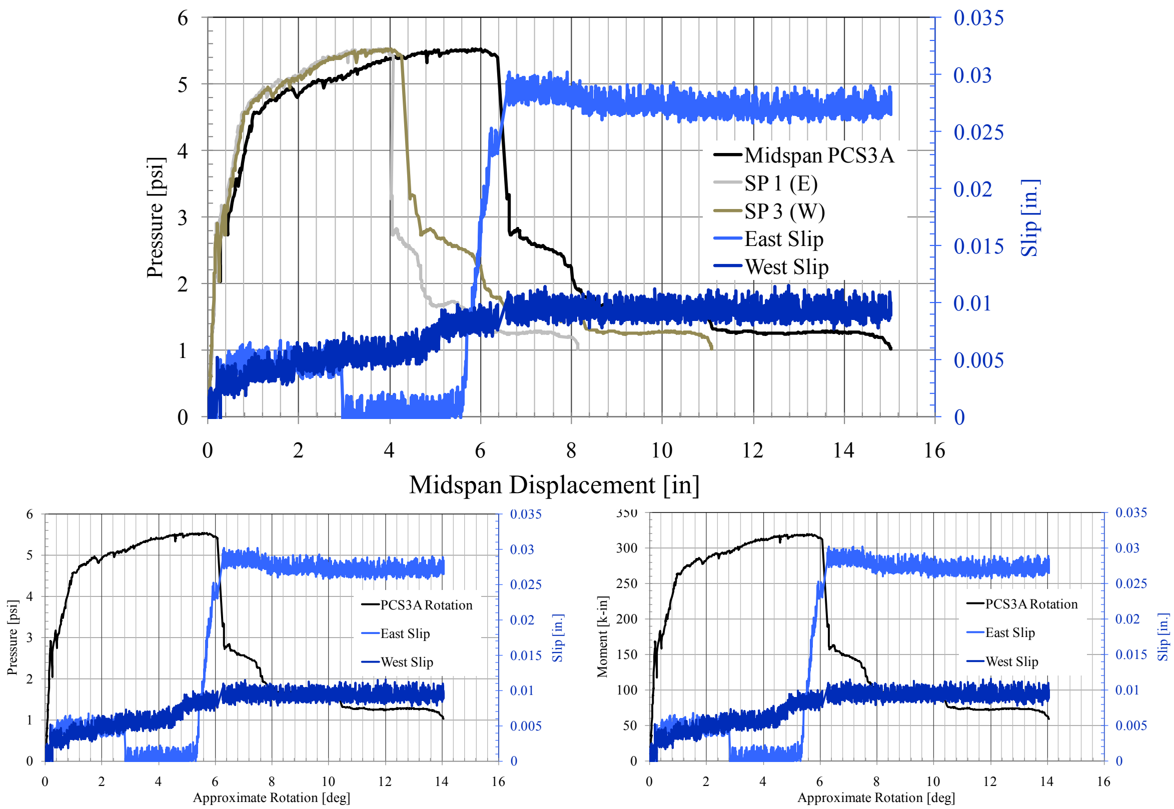


Figure 72. PCS3-A Response

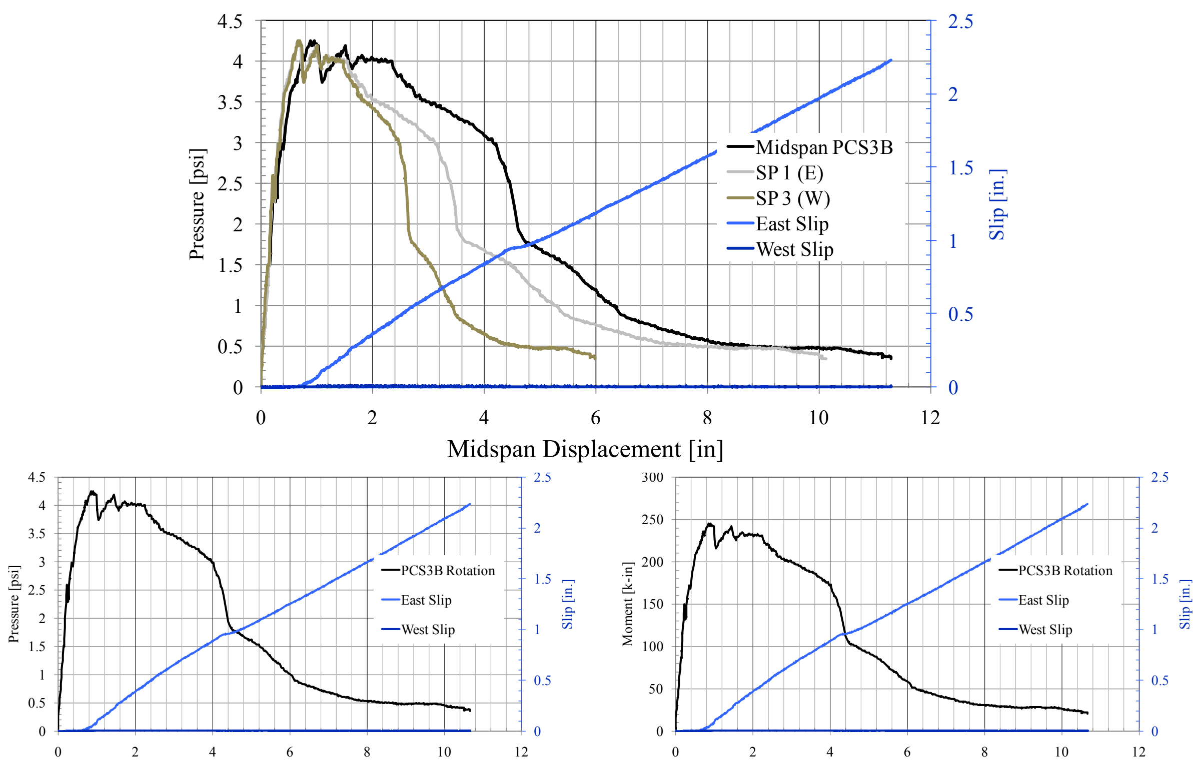


Figure 73. PCS3-B Response


Distribution Statement A: Approved for public release; distribution unlimited.

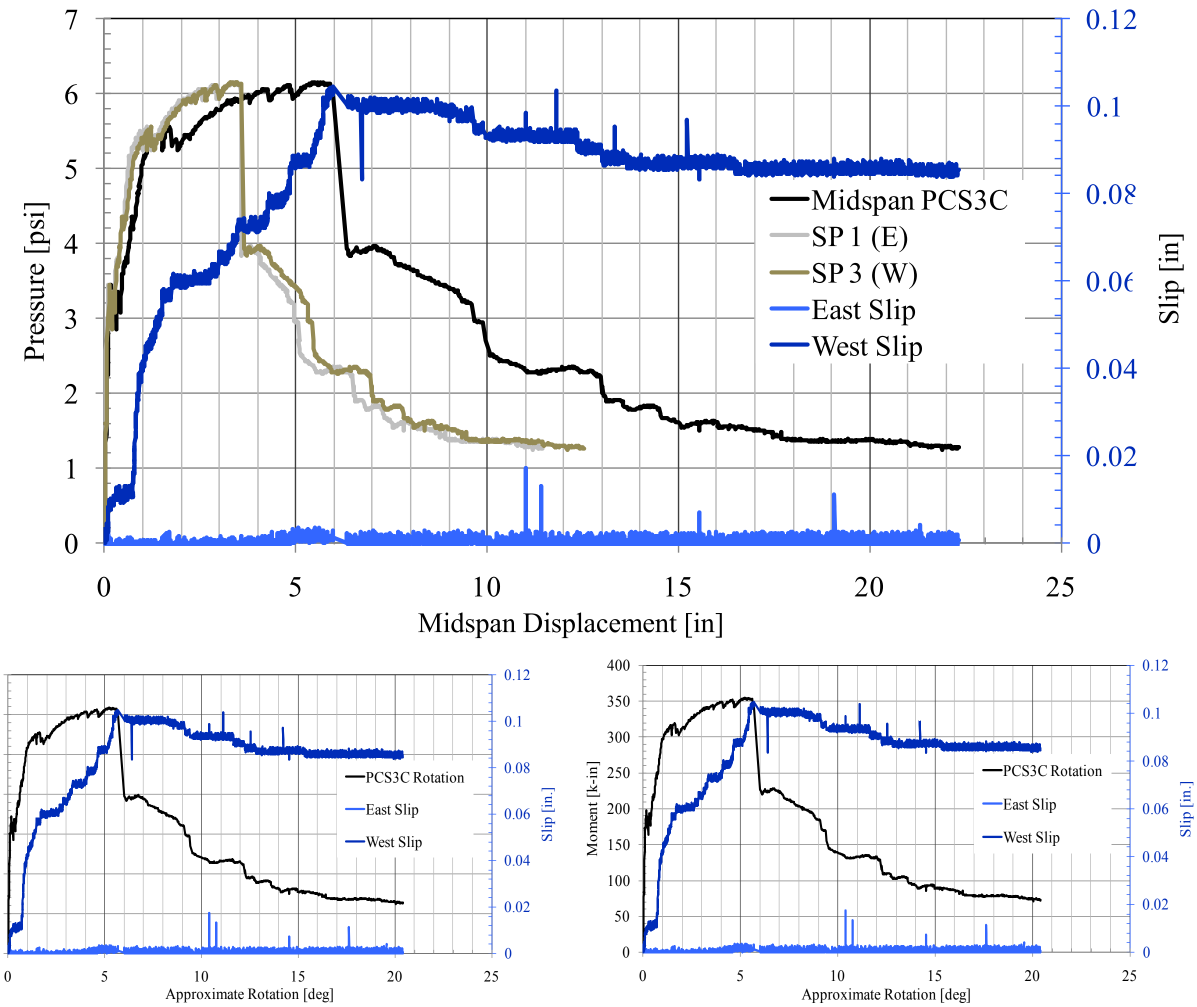


**Figure 74. PCS3-C Response**

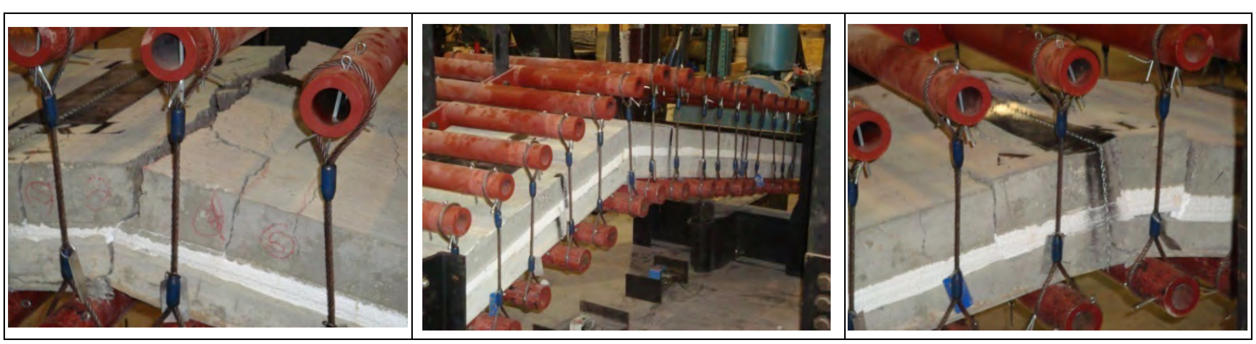

**Figure 75. PCS3 Panel Response (A, B, C)**


Distribution Statement A: Approved for public release; distribution unlimited.

### 6.6. PCS3 (Type 2) 3-2-3 Specimen Performance

PCS3 (Type 2) consists of a partially composite 3-2-3 PC CSW panel fabricated with EPS insulation and steel C-clip shear ties. The panel contains both prestressing and conventional non-PS longitudinal reinforcement with WWR transverse reinforcement in both the interior and exterior wythe. The panel cross-section and reinforcement details are illustrated in Figures 76 and 77.

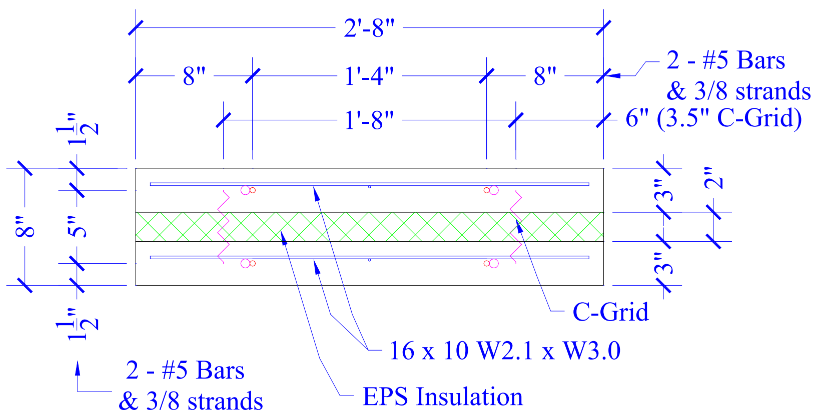


**Figure 76. PCS3 (Type 2) Cross-Section Detail**

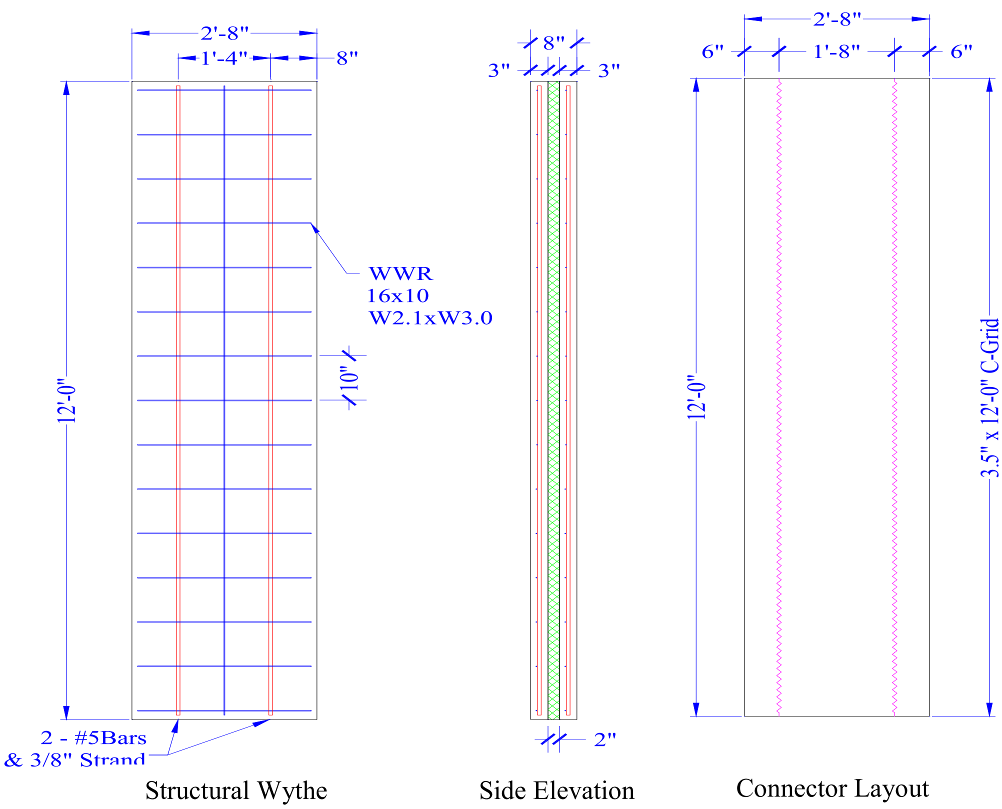


**Figure 77. PCS3 (Type 2) Panel Detail**



Distribution Statement A: Approved for public release; distribution unlimited.

The measured response is summarized in Table 21. The midspan pressure displacement and moment–support rotation for the three specimen are in Figures 78 and 79. The individual response of each panel and the end slip and quarter point displacements are included in Figures 80-82. Figure 83 shows a picture representation of the samples post-test.

**Table 21. PCS3 (Type 2) Measured Response**

| Specimen | Age at Test [days] | Max Load [lbs] | Max Pressure [psi] | Corresponding Displacement [in] | East Slip [in] | West Slip [in] | Rot. [deg] | Measured Moment Capacity [k-in] |
|---|---|---|---|---|---|---|---|---|
| PCS3-D | 36 | 21886 | 5.699 | 5.544 | 0.695 | 0.368 | 5.279 | 328.28 |
| PCS3-E | 43 | 23645 | 6.157 | 5.320 | 0.652 | 0.358 | 5.067 | 354.67 |
| PCS3-F | 43 | 20956 | 5.457 | 3.896 | 0.000 | 0.762 | 3.716 | 314.34 |
| | Average | 22162 | 5.77 | 4.92 | 0.45 | 0.50 | 4.69 | 332.4 |

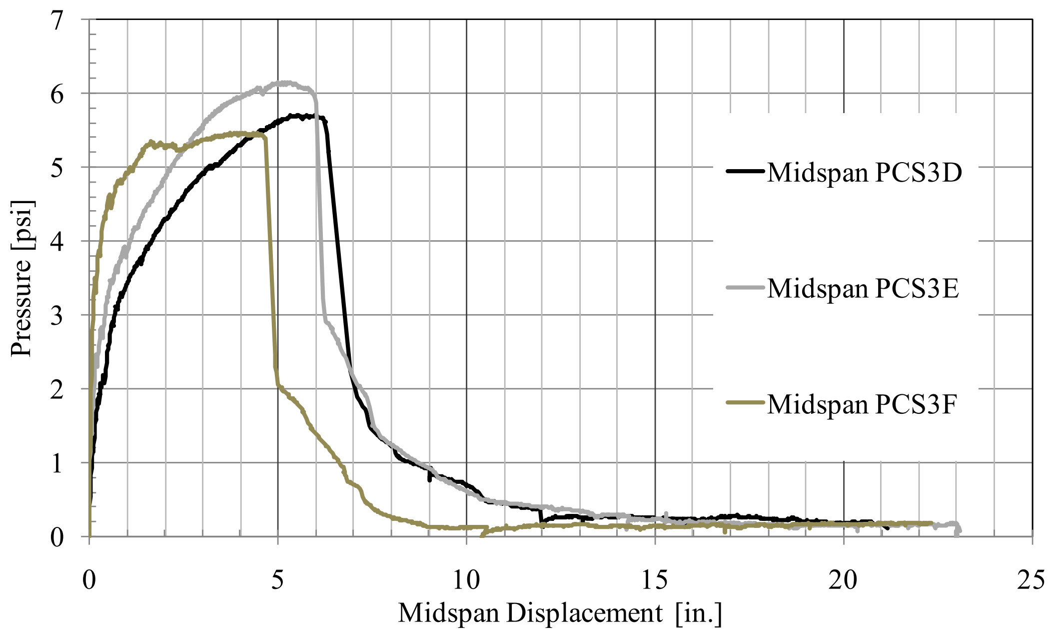

**Figure 78. PCS3 (Type 2) Pressure–Displacement Response**


Distribution Statement A: Approved for public release; distribution unlimited.

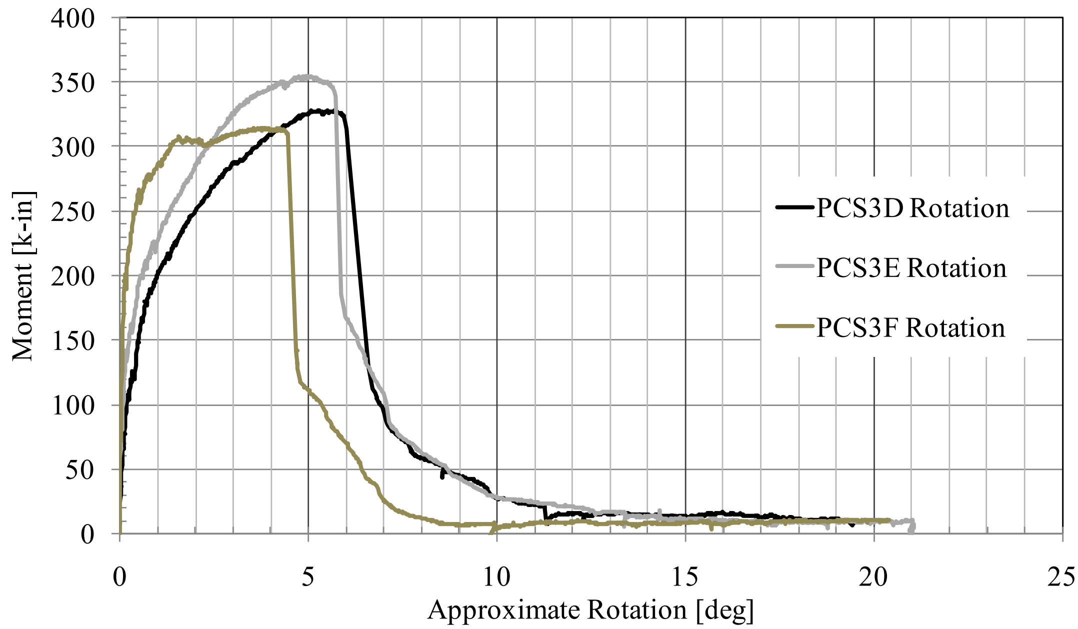


**Figure 79. PCS3 (Type 2) Moment–Rotation Response**

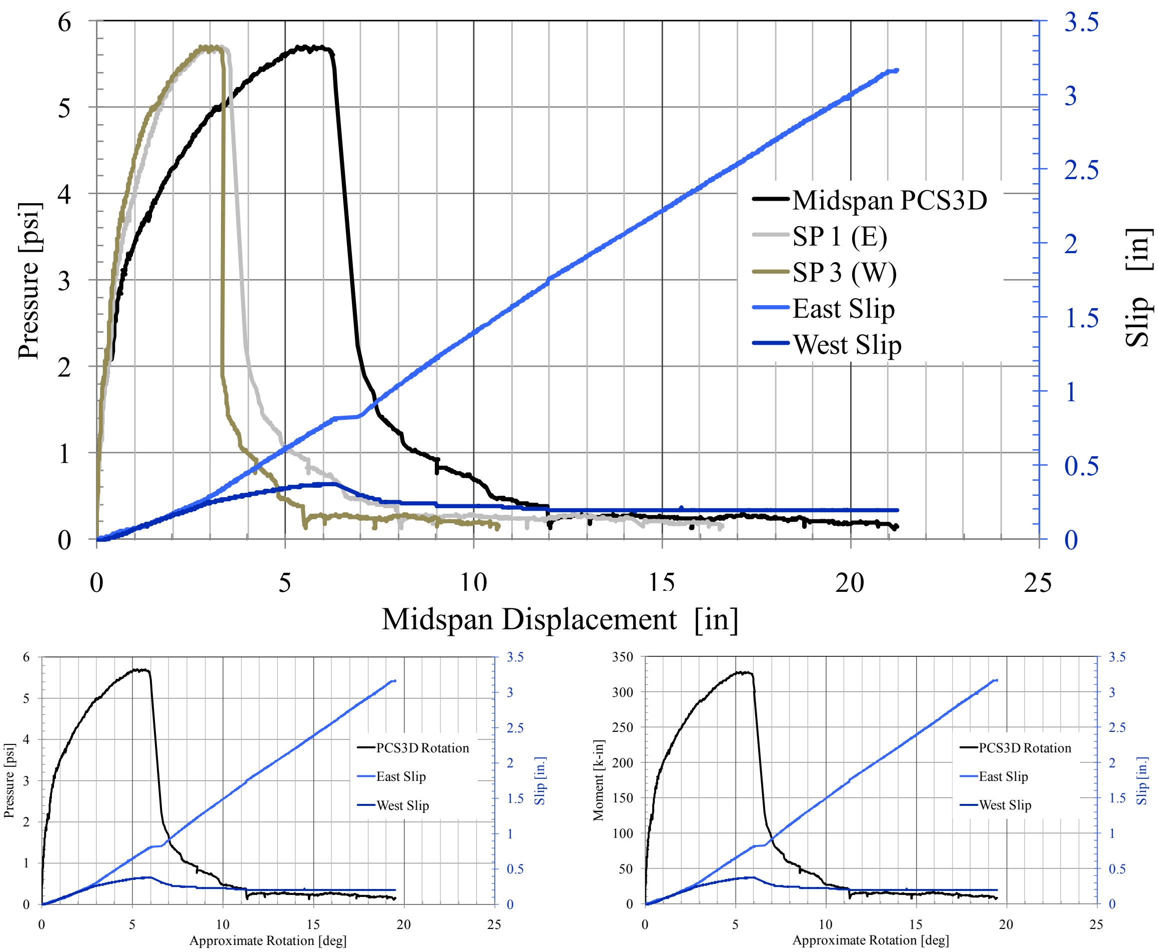


**Figure 80. PCS3-D Response**



Distribution Statement A: Approved for public release; distribution unlimited.

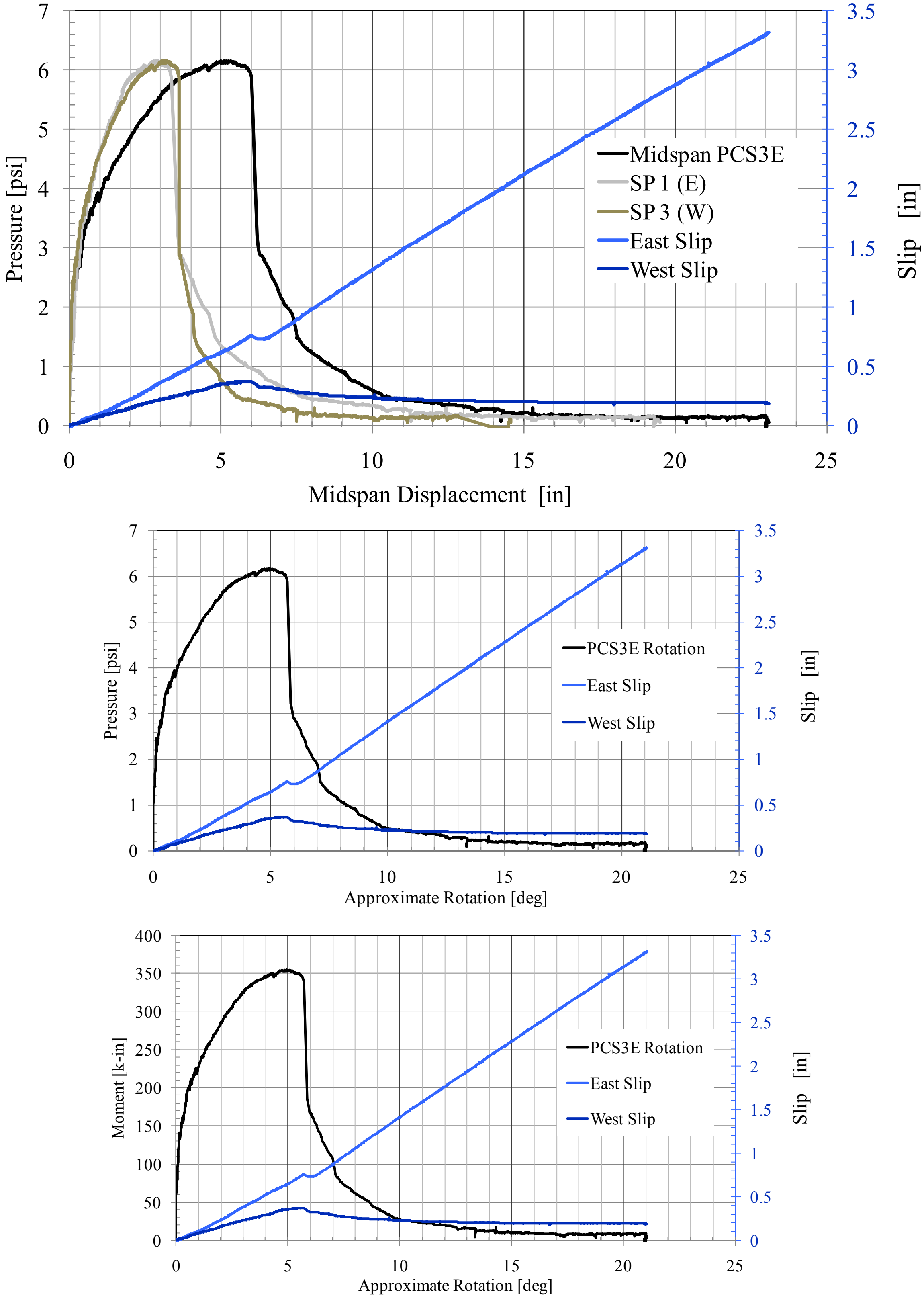


**Figure 81. PCS3-E Response**


Distribution Statement A: Approved for public release; distribution unlimited.

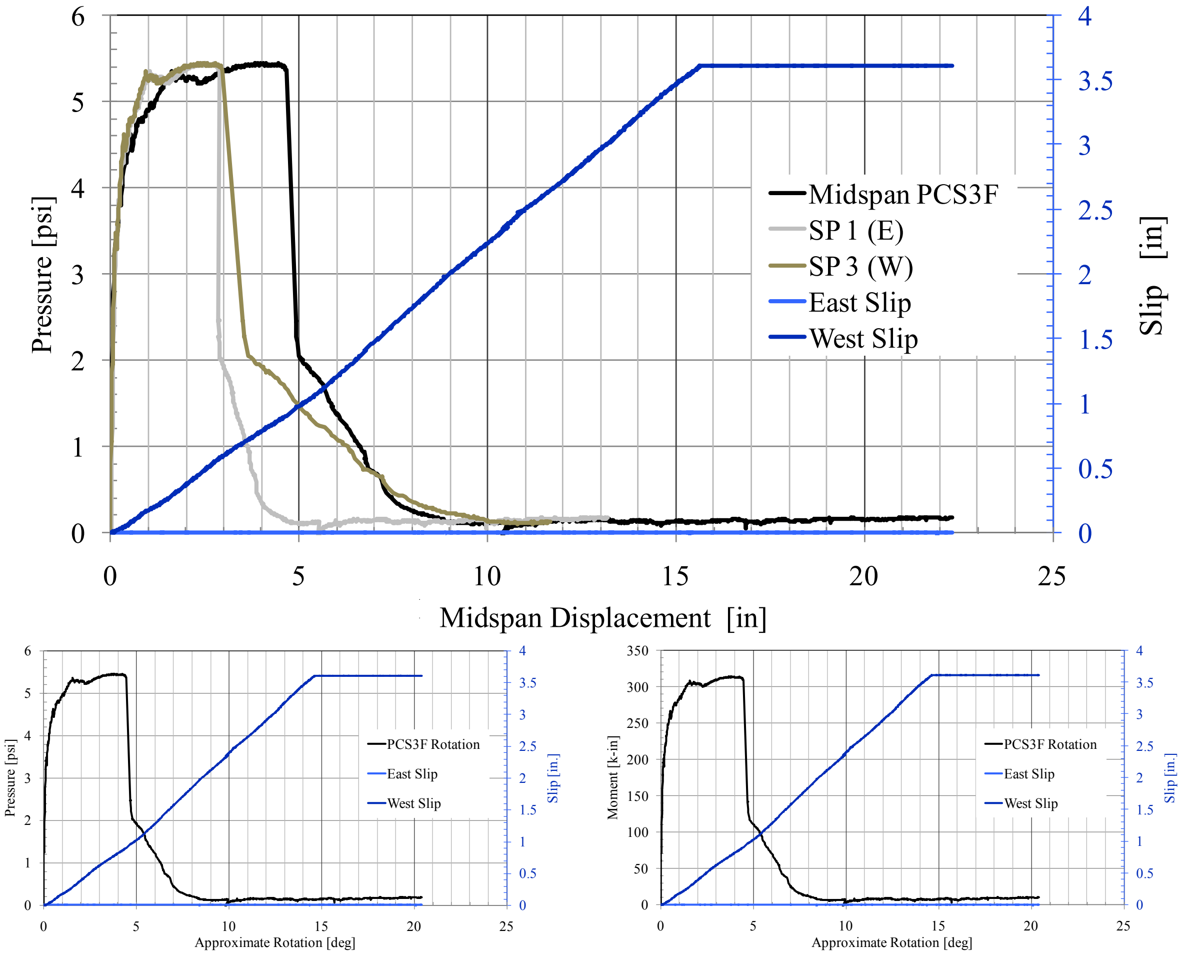


**Figure 82. PCS3-F Response**

**Figure 83. PCS3 (Type 2) Panel Response (D, E, F)**

### 6.7. PCS4 3-3-3 Specimen Performance

PCS4 consists of a partially composite 3-3-3 PC CSW panel fabricated with XPS insulation and steel C-clip shear ties. The panel is PS with rebar transverse reinforcement in both the interior and exterior wythe. The panel cross-section and reinforcement details are illustrated in Figures 84-86.


Distribution Statement A: Approved for public release; distribution unlimited.

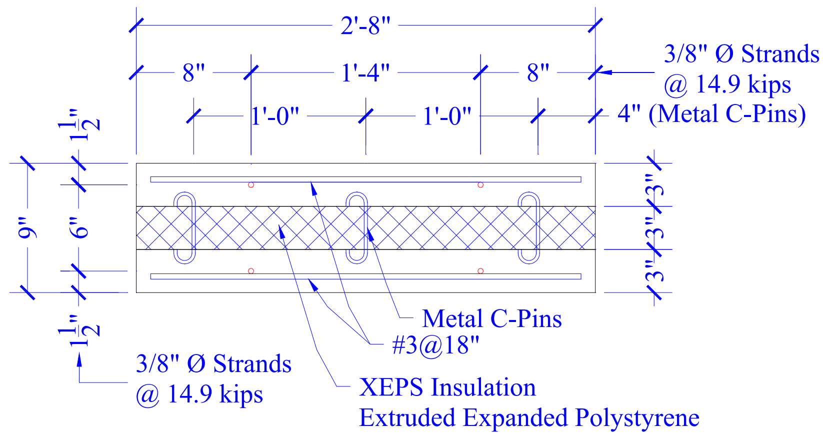


**Figure 84. PCS4 Cross-Section Detail**

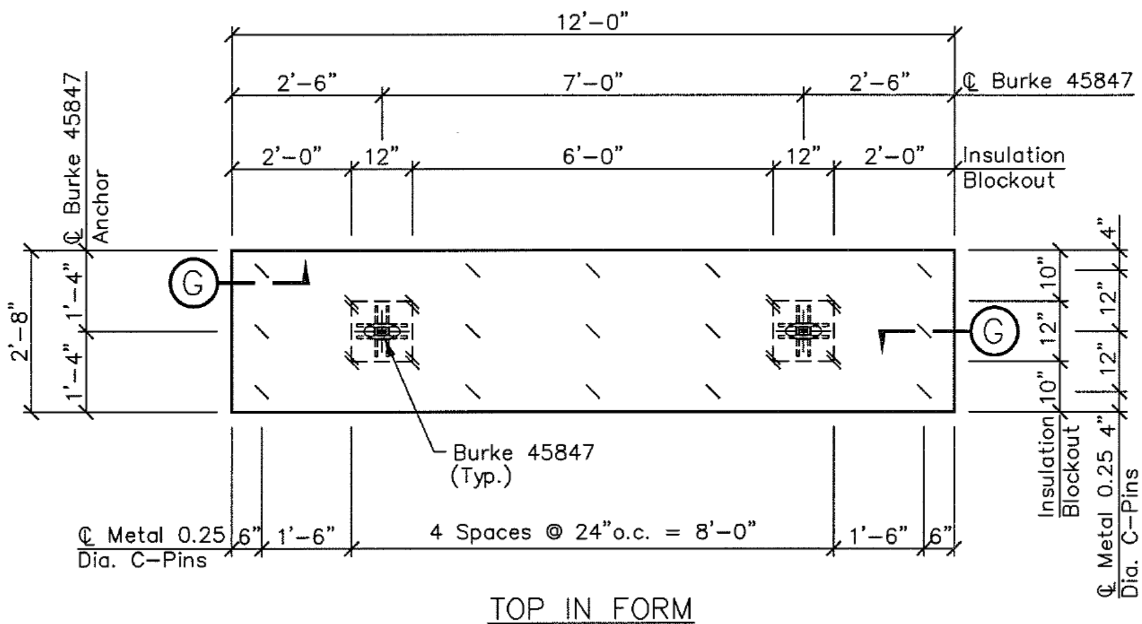


**Figure 85. PCS4 Panel Detail**

The material properties for the specimen and the measured response are summarized in Table 22 and Table 23. The midspan pressure displacement and moment–support rotation for the three specimen follow in Figures 87 and 88. The individual response of each panel and the quarter point displacements are included at the end in Figures 89-91. Figure 92 shows a picture representation of the three samples post-test.


Distribution Statement A: Approved for public release; distribution unlimited.

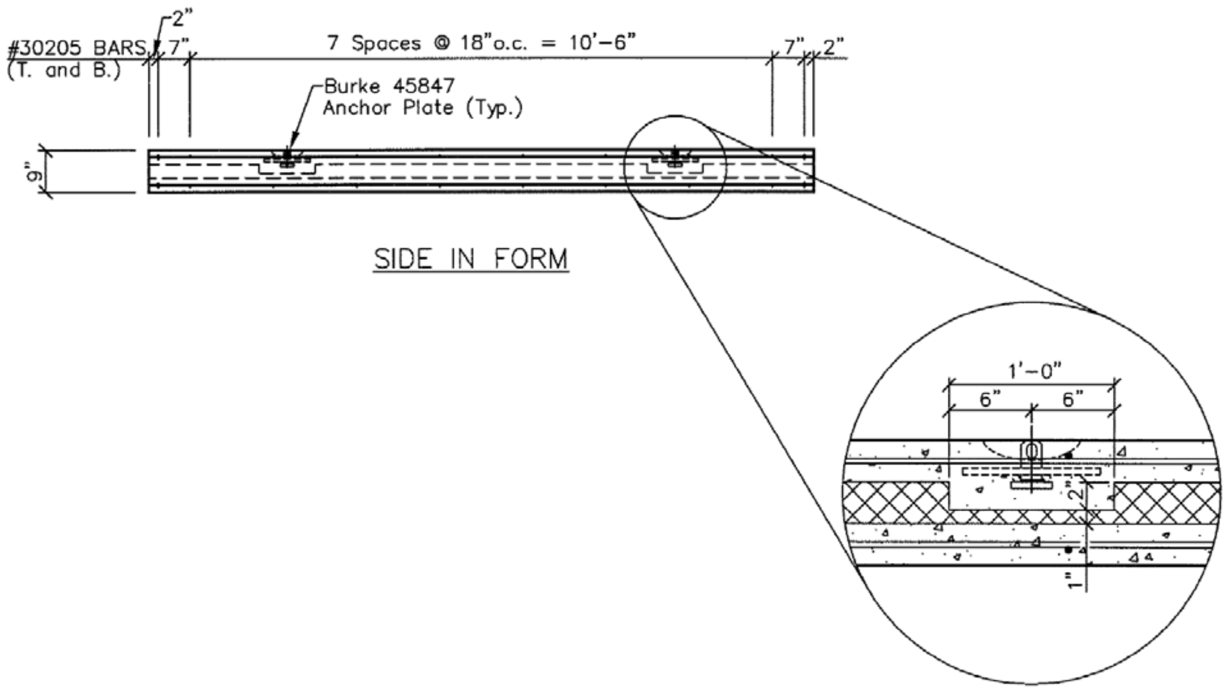


**Figure 86. PCS4 Panel Detail 2**

**Table 22. PCS4 Material Properties**

| Property | Value |
|---|---|
| Design Unit Weight | 150 lb/ft$^3$ |
| Design Compression Strength at Release, $f_{ci}$ | 3500 psi |
| Design Compressive Strength at 28 days. $f'_c$ | 5000 psi |
| Approximate Compressive Strength PCS4-A | 8873 psi |
| Approximate Compressive Strength PCS4-B | 8793 psi |
| Approximate Compressive Strength PCS4-C | 8793 psi |

**Table 23. PCS4 Measured Response**

| Specimen | Age at Test [days] | Max Load [lbs] | Max Pressure [psi] | Corresponding Displacement [in] | East Slip [in] | West Slip [in] | Rot. [deg] | Measured Moment Capacity [k-in] |
|---|---|---|---|---|---|---|---|---|
| PCS4-A | 100 | 18410 | 4.794 | 6.943 | 0.673 | 0.897 | 6.601 | 276.14 |
| PCS4-B | 109 | 16138 | 4.203 | 5.408 | 0.250 | 0.974 | 5.151 | 242.07 |
| PCS4-C | 109 | 19110 | 4.976 | 6.355 | 0.512 | 0.909 | 6.046 | 286.65 |
| | Average | 17886 | 4.66 | 6.24 | 0.48 | 0.93 | 5.93 | 268.3 |


Distribution Statement A: Approved for public release; distribution unlimited.

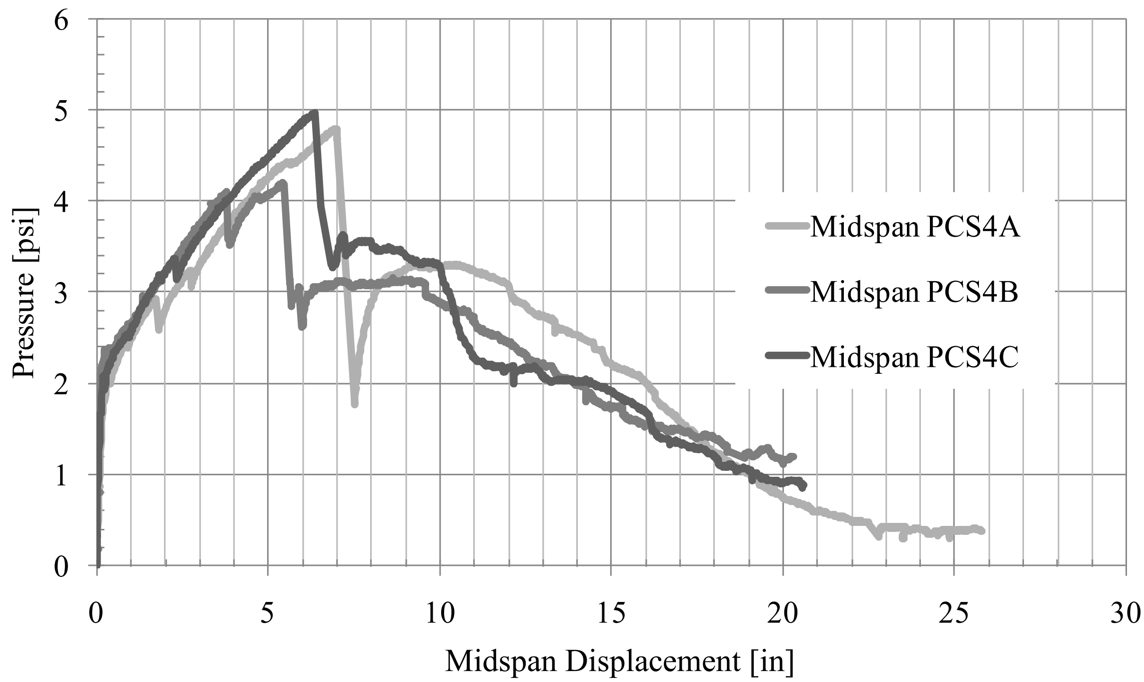


**Figure 87. PCS4 Pressure–Displacement Response**

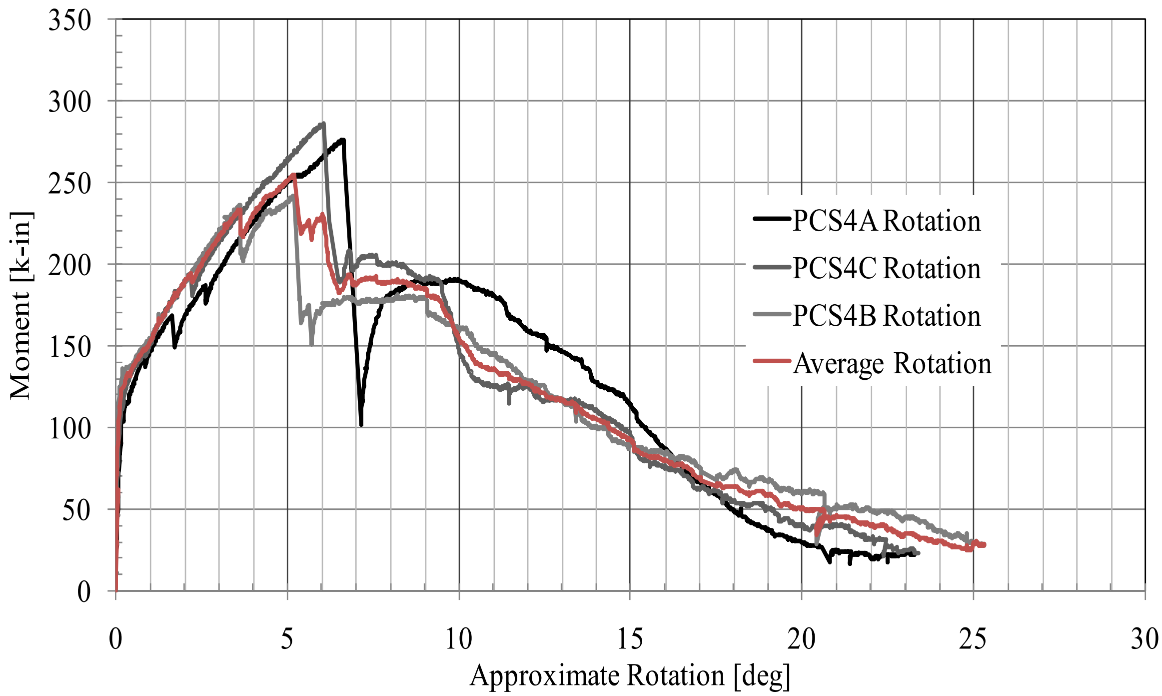


**Figure 88. PCS4 Moment–Rotation Response**


Distribution Statement A: Approved for public release; distribution unlimited.

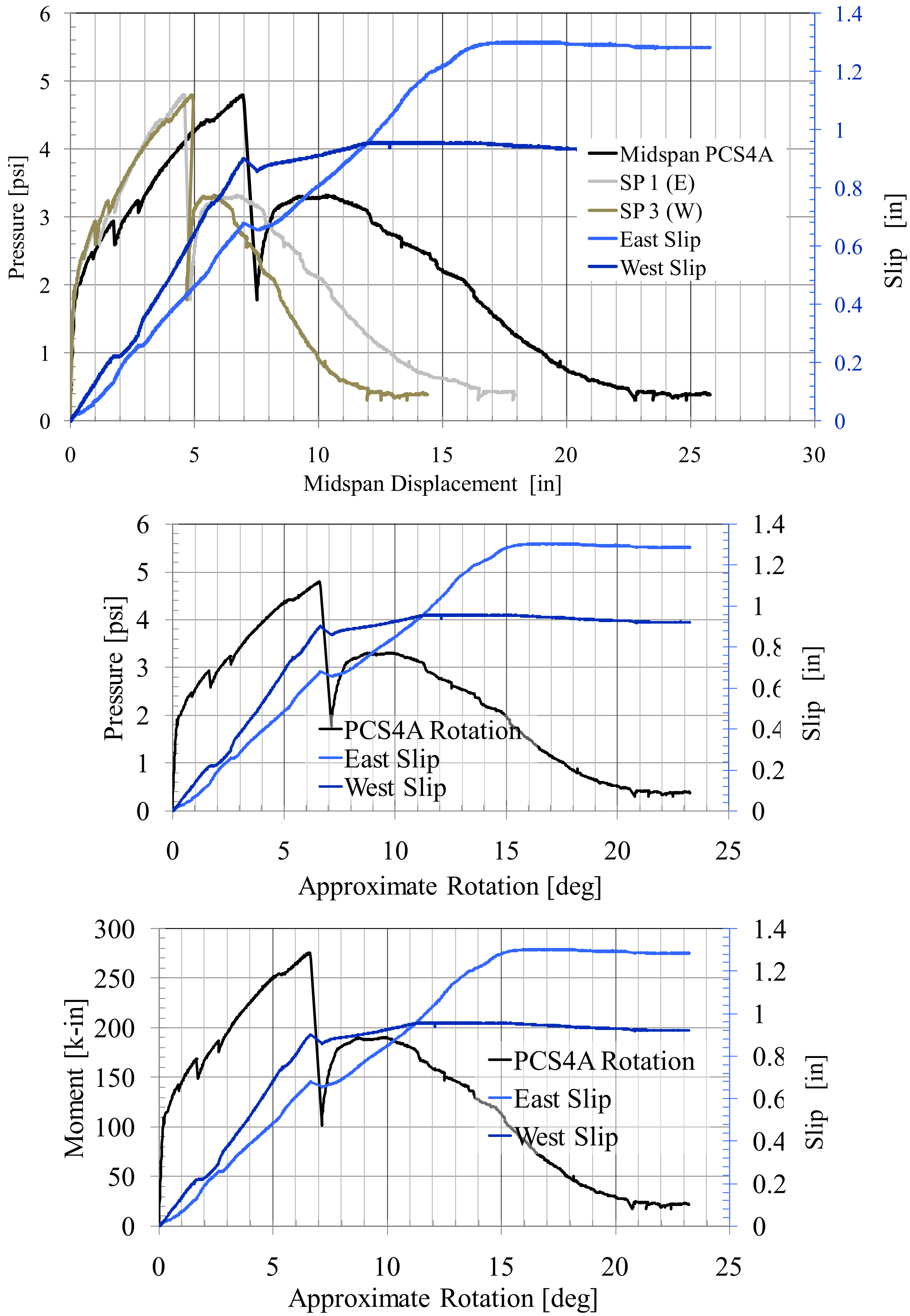

**Figure 89. PCS4-A Response**

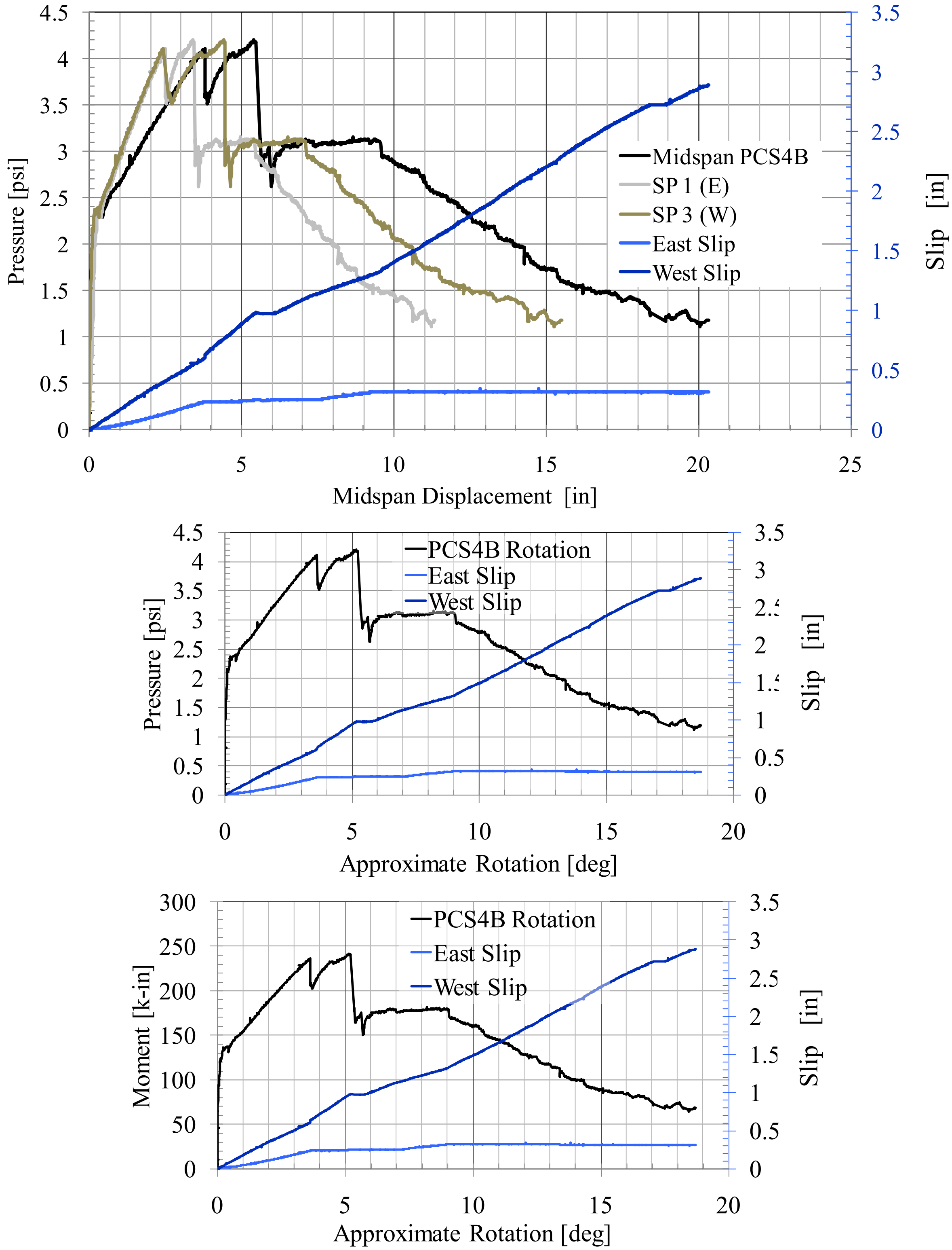


**Figure 90. PCS4-B Response**


Distribution Statement A: Approved for public release; distribution unlimited.

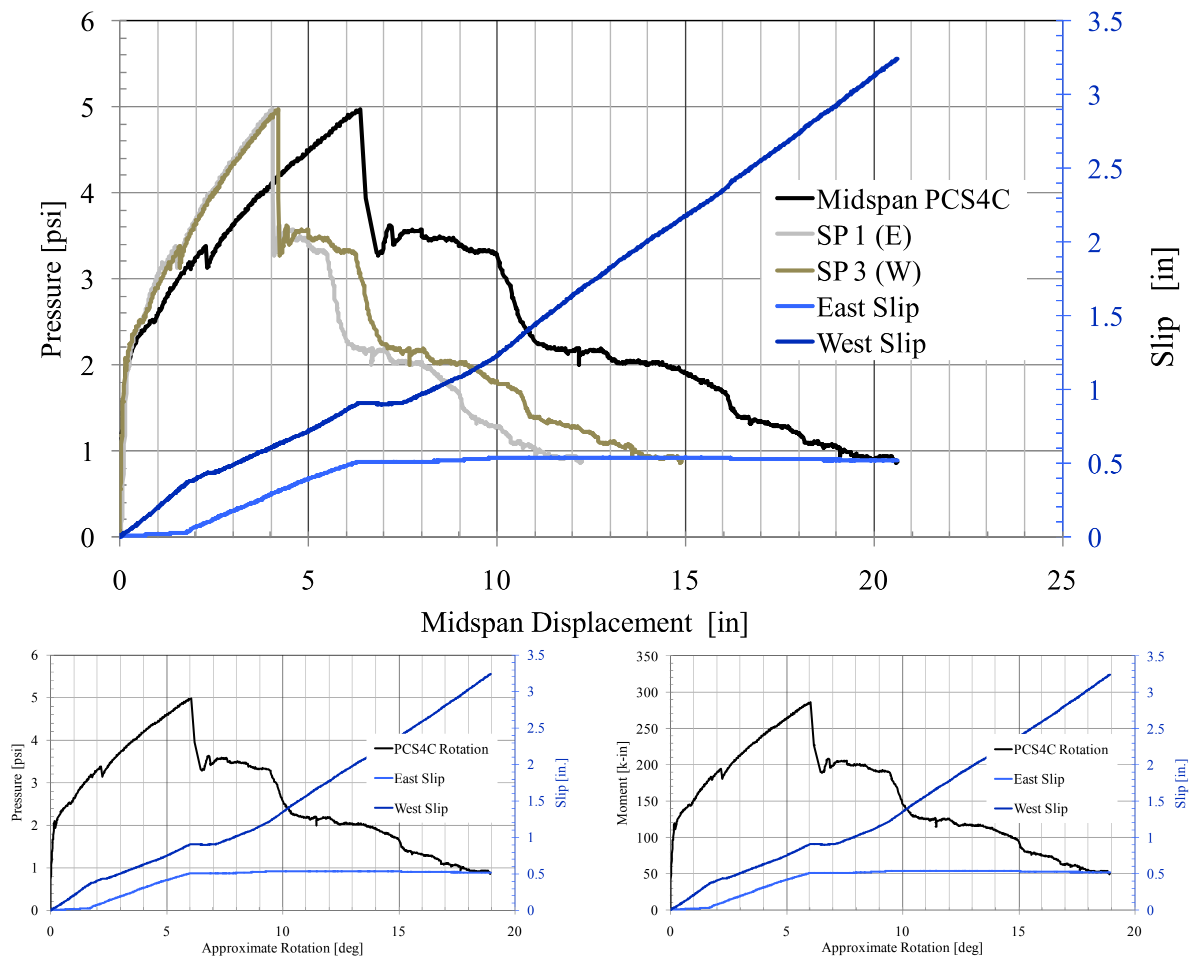


**Figure 91. PCS4-C Response**

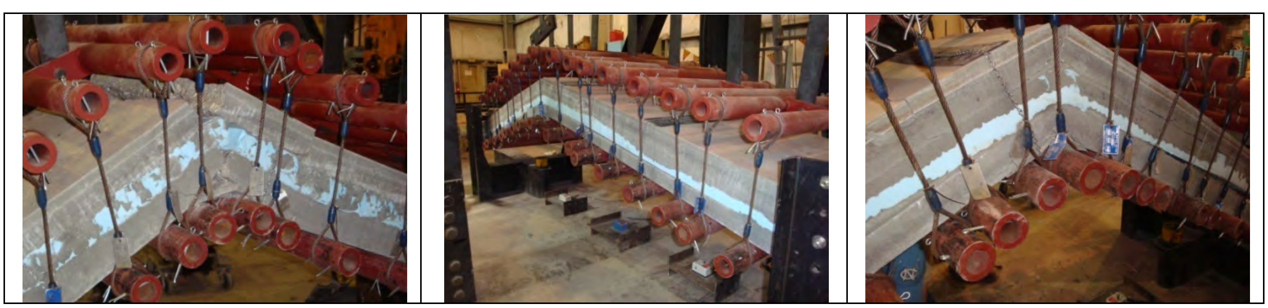

**Figure 92. PCS4 Panel Response (A, B, C)**

## 6.8. PCS5 3-3-3 Specimen Performance

PCS5 consists of a partially composite 3-3-3 PC CSW panel fabricated with XPS insulation and glass fiber THERMOMASS® composite shear pins. The panel is PS with rebar transverse reinforcement in both the interior and exterior wythe. The panel cross-section and reinforcement details are illustrated in Figures 93 and 94.


Distribution Statement A: Approved for public release; distribution unlimited.

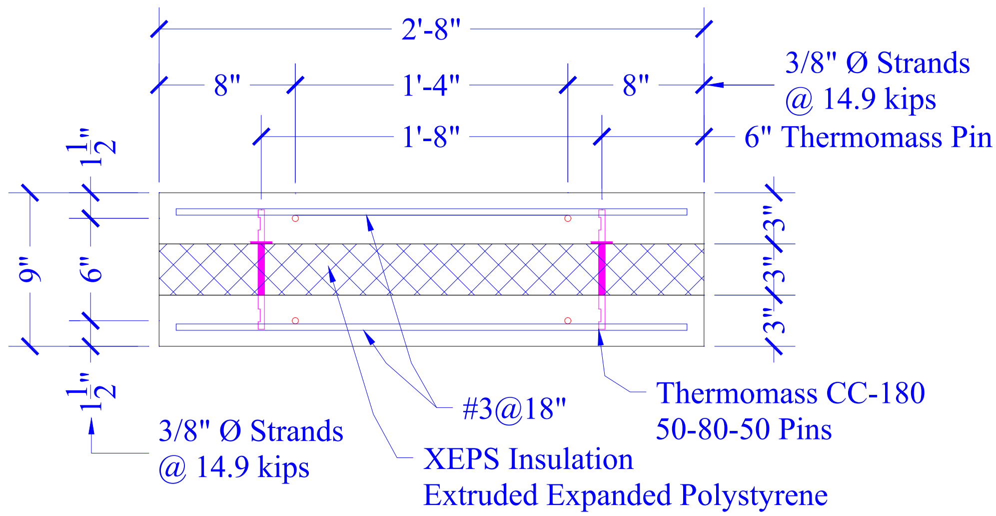


**Figure 93. PCS5 Cross-Section Detail**

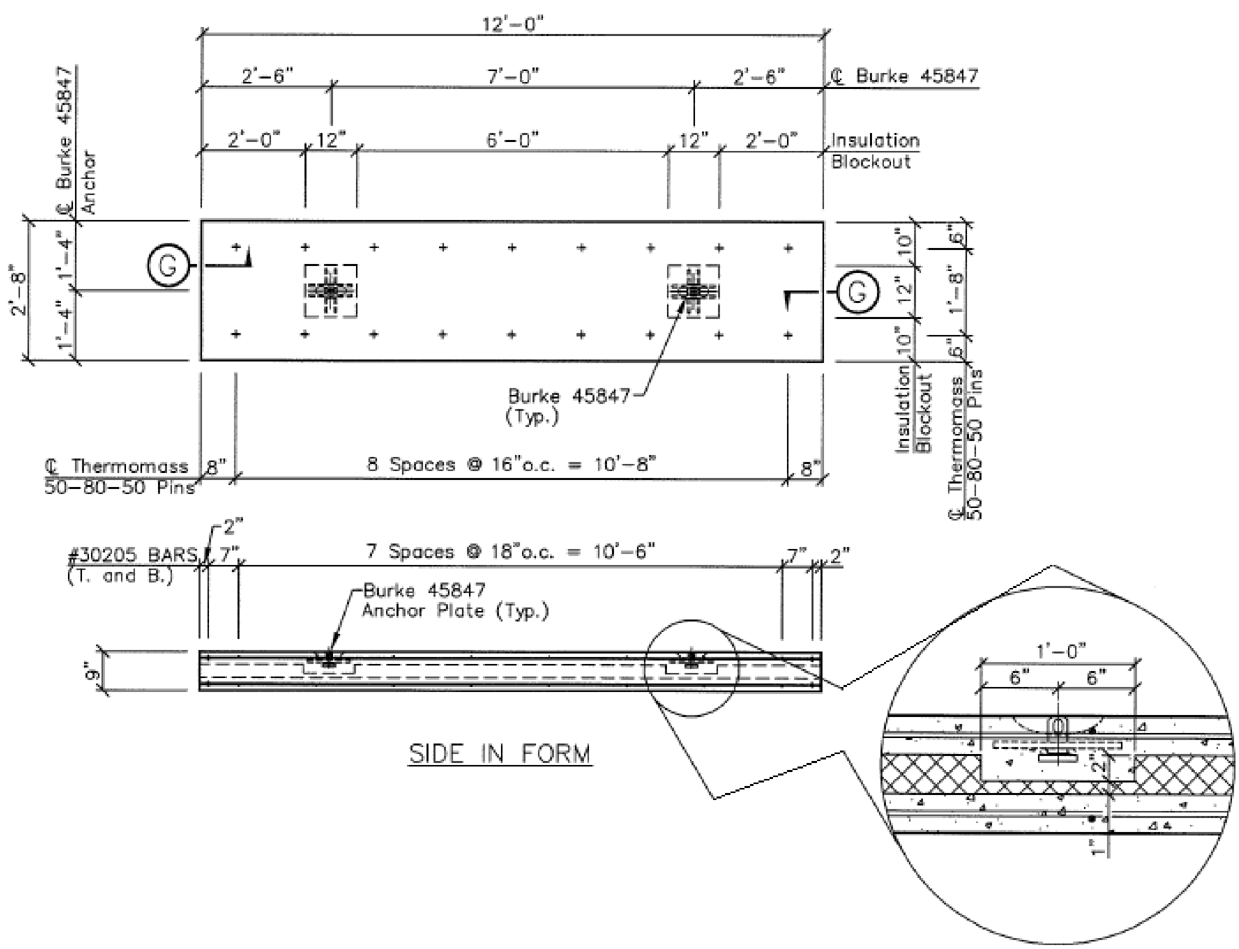


**Figure 94. PCS5 Panel Detail**


Distribution Statement A: Approved for public release; distribution unlimited.

The measured response is summarized in Table 24. The midspan pressure displacement and moment–support rotation for the three specimen are in Figures 95 and 96. The individual response of each panel and the end slip and quarter point displacements are included in Figures 97-99. Figure 100 shows a picture representation of the samples post-test.

**Table 24. PCS5 Measured Response**

| Specimen | Age at Test [days] | Max Load [lbs] | Max Pressure [psi] | Corresponding Displacement [in] | East Slip [in] | West Slip [in] | Rot. [deg] | Measured Moment Capacity [k-in] |
|---|---|---|---|---|---|---|---|---|
| PCS5-A | 101 | 17770 | 4.628 | 4.765 | 0.527 | 0.604 | 4.541 | 266.55 |
| PCS5-B | 112 | 19910 | 5.185 | 5.118 | 0.500 | 0.562 | 4.875 | 298.65 |
| PCS5-C | 113 | 18252 | 4.753 | 5.536 | 0.633 | 0.637 | 5.272 | 273.78 |
| | Average | 18644 | 4.86 | 5.14 | 0.55 | 0.60 | 4.90 | 279.7 |

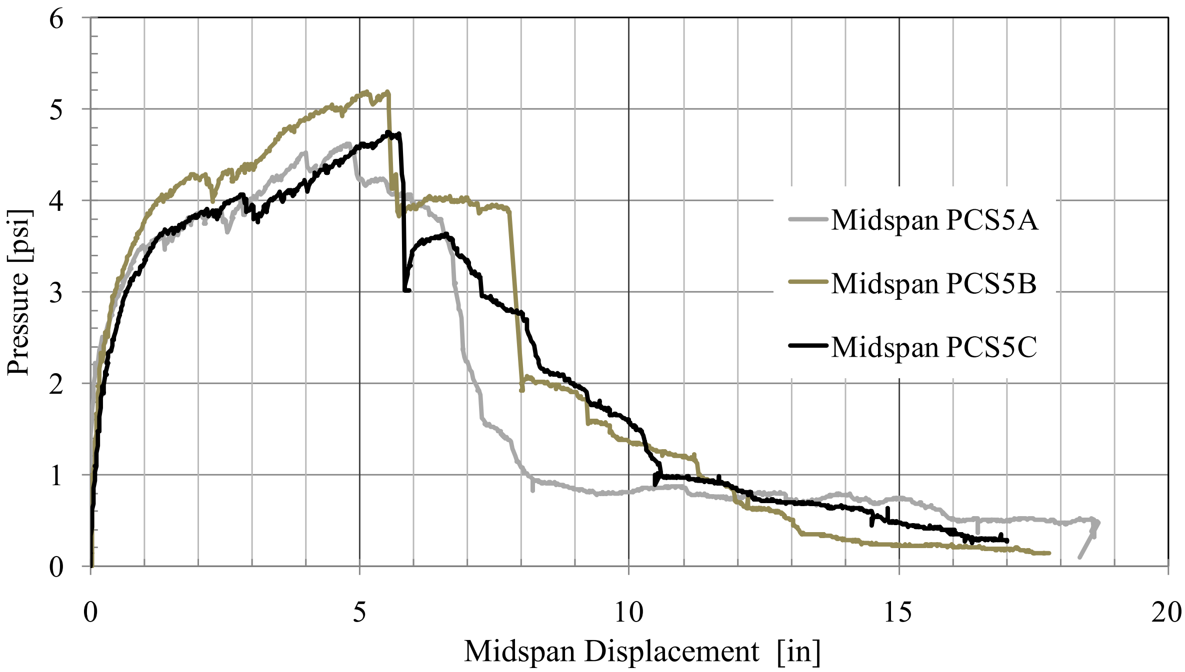


**Figure 95. PCS5 Pressure–Displacement Response**


Distribution Statement A: Approved for public release; distribution unlimited.

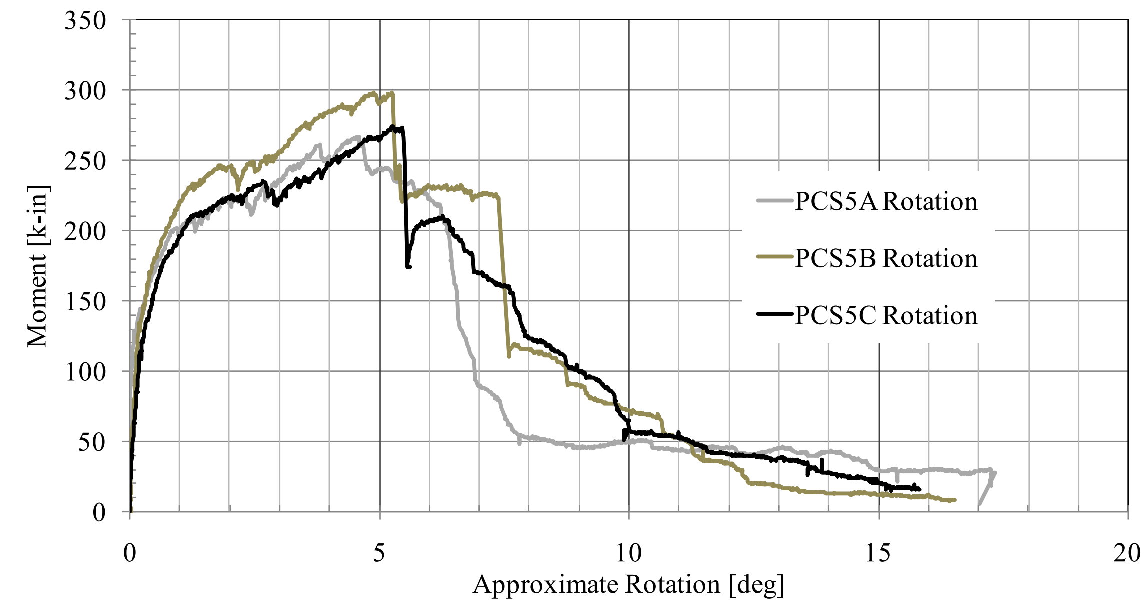


**Figure 96. PCS5 Moment–Rotation Response**

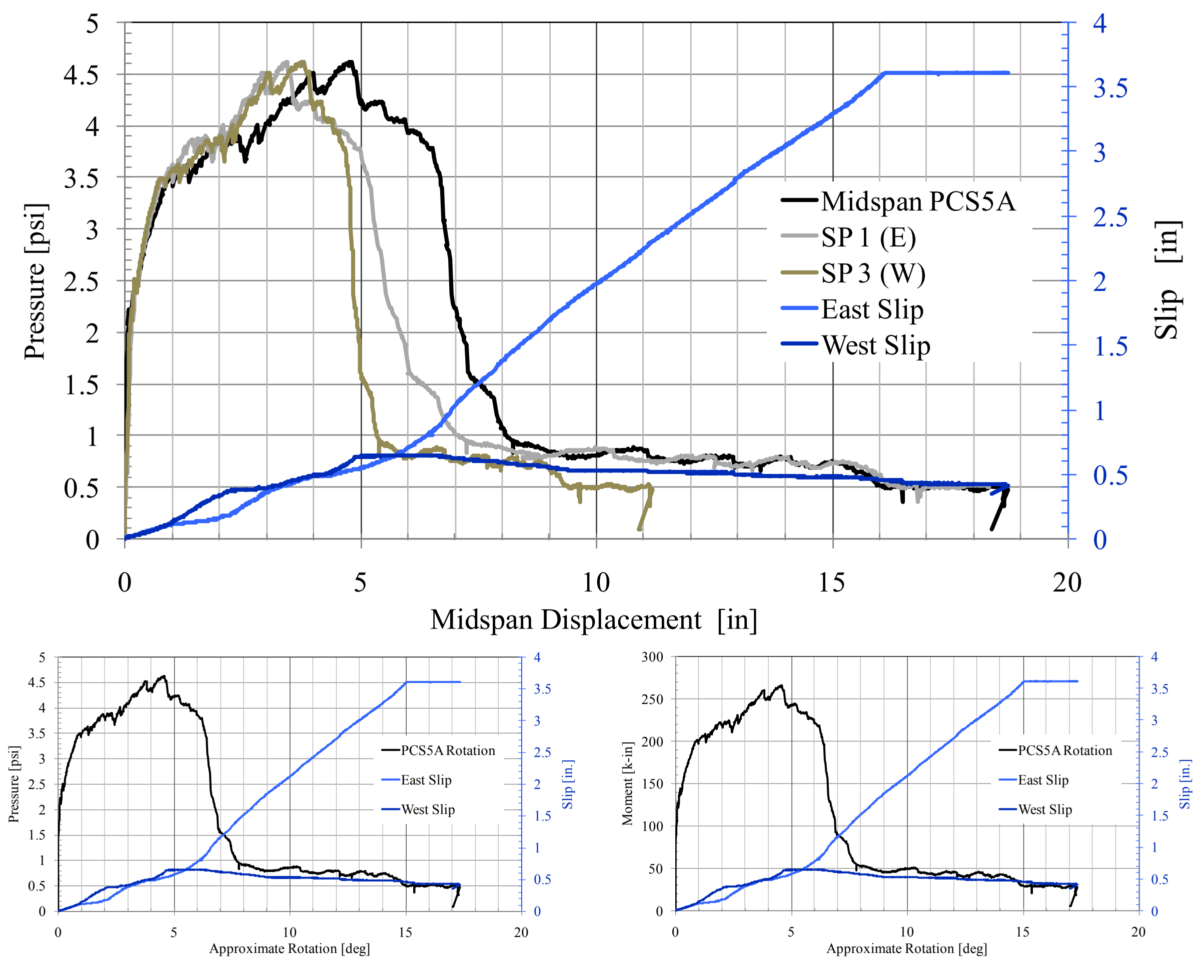


**Figure 97. PCS5-A Response**



Distribution Statement A: Approved for public release; distribution unlimited.

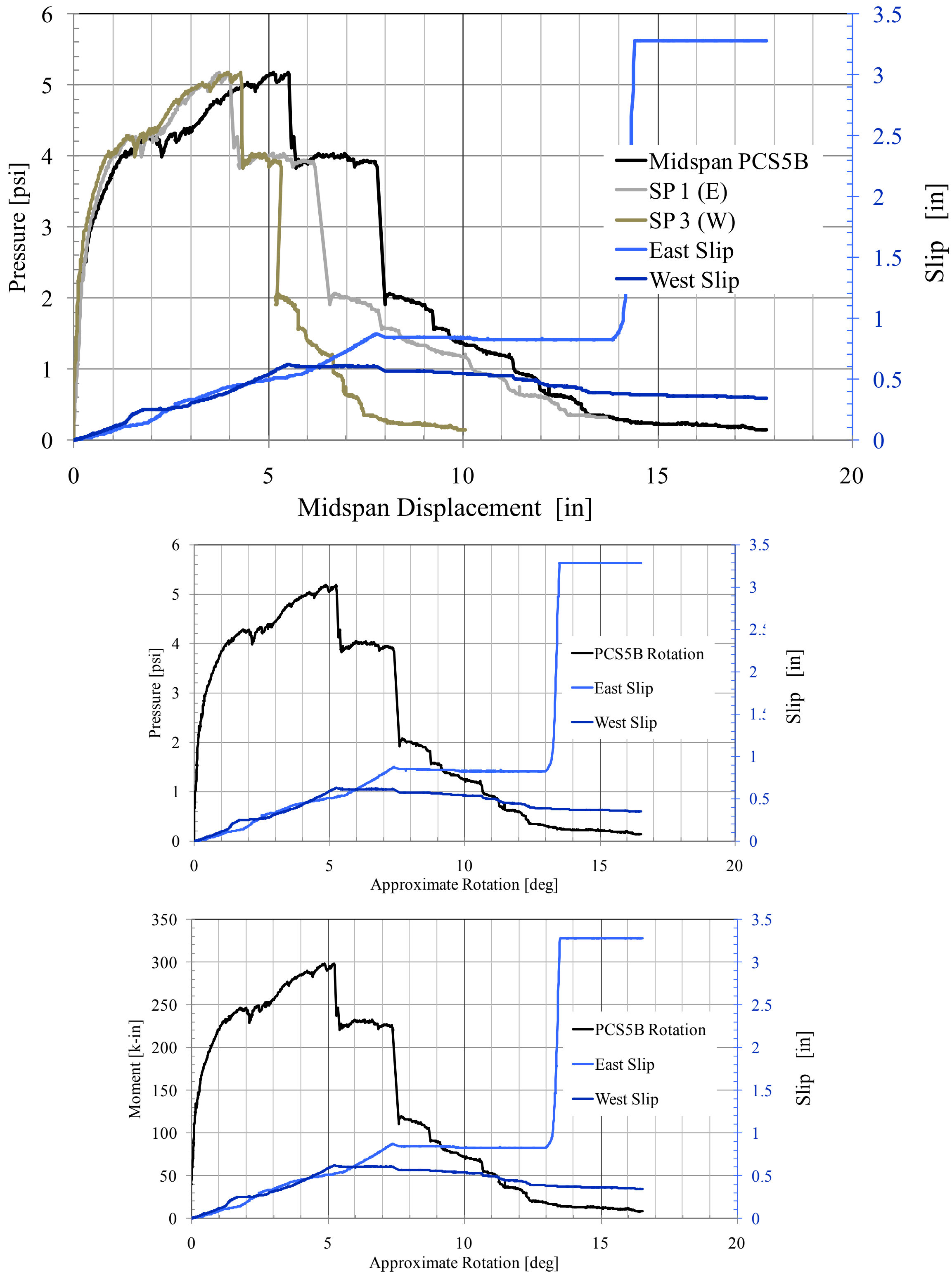


**Figure 98. PCS5-B Response**


Distribution Statement A: Approved for public release; distribution unlimited.

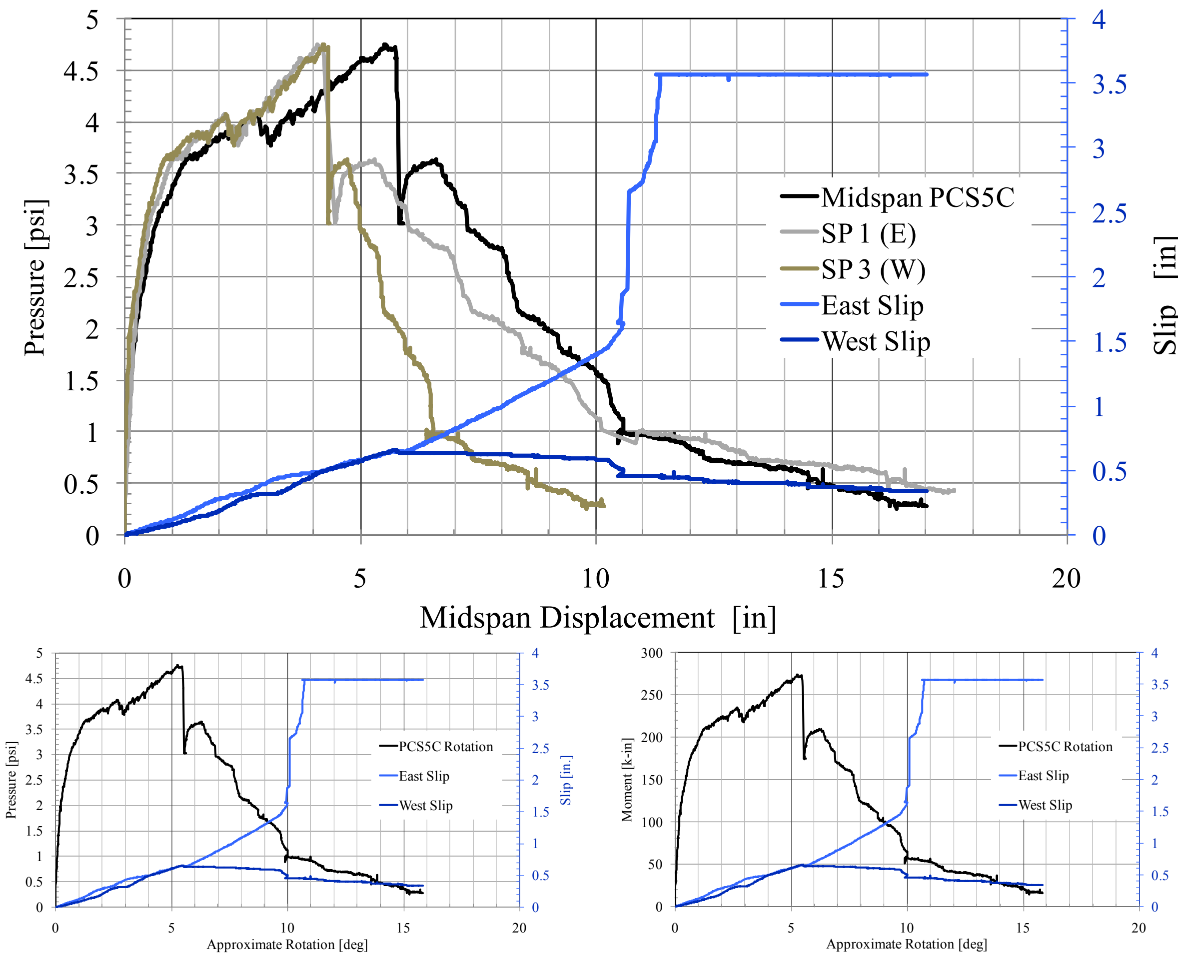


**Figure 99. PCS5-C Response**

**Figure 100. PCS5 Panel Response (A, B, C)**

## 6.9. PCS6 3-3-3 Specimen Performance

PCS6 consists of a partially composite 3-3-3 PC CSW panel fabricated with XPS insulation and carbon fiber C-Grid® shear ties. The panel is PS with WWR transverse reinforcement in both the interior and exterior wythe. The panel cross-section and reinforcement details are illustrated in Figures 101 and 102.


Distribution Statement A: Approved for public release; distribution unlimited.

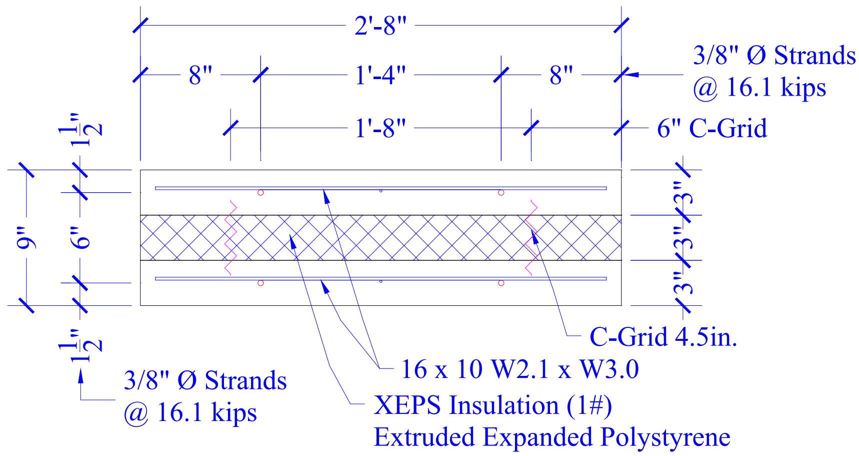


**Figure 101. PCS6 Cross-Section Detail**

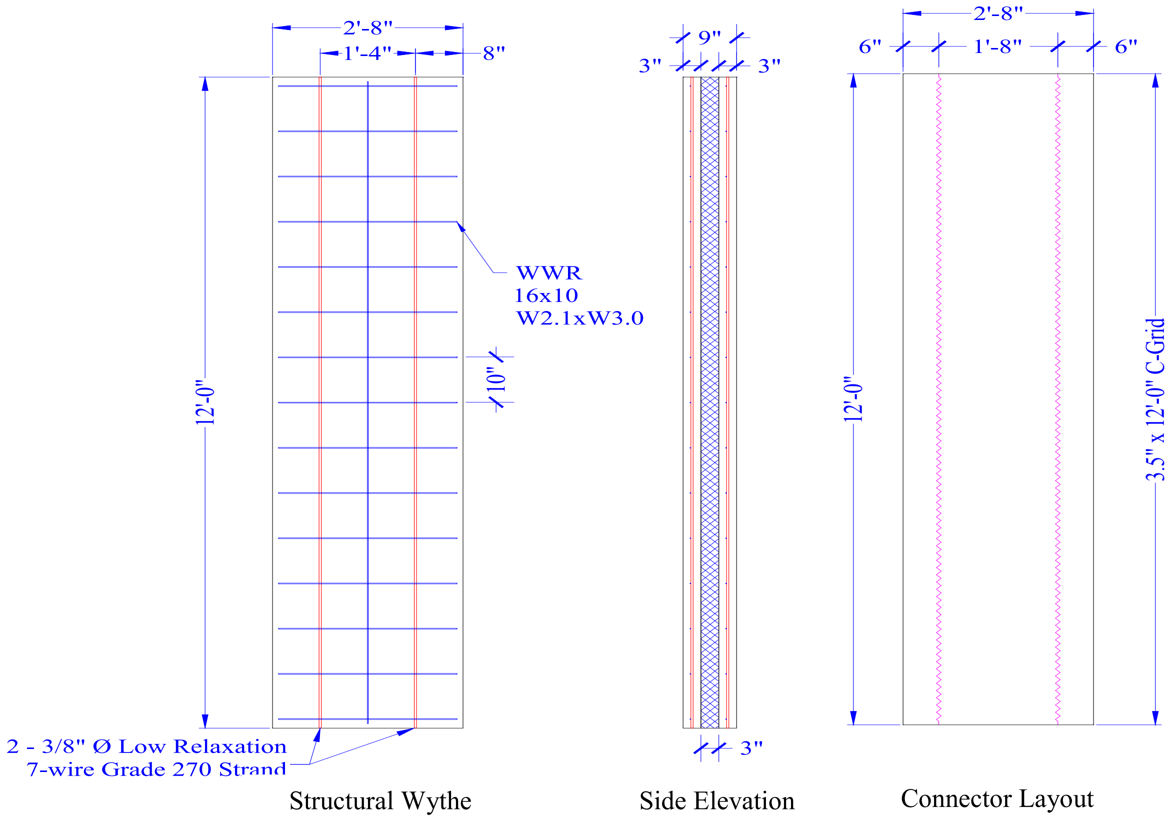


**Figure 102. PCS6 Panel Detail**

The measured response is summarized in Table 25. The midspan pressure displacement and moment-support rotation for the three specimen are in Figures 103 and 104. The individual response of each panel and the end slip and quarter point displacements are included in Figures 105-107. Figure 108 shows a picture representation of the samples post-test.


Distribution Statement A: Approved for public release; distribution unlimited.

**Table 25. PCS6 Measured Response**

| Specimen | Age at Test [days] | Max Load [lbs] | Max Pressure [psi] | Corresponding Displacement [in] | East Slip [in] | West Slip [i.] | Rot. [deg] | Measured Moment Capacity [k-in] |
|---|---|---|---|---|---|---|---|---|
| PCS6-A | 37 | 18581 | 4.839 | 3.644 | 0.502 | 0.504 | 3.475 | 278.71 |
| PCS6-B | 45 | 18146 | 4.726 | 2.945 | 0.443 | 0.236 | 2.810 | 272.19 |
| PCS6-C | 45 | 13233 | 3.446 | 2.061 | 0.021 | 0.413 | 1.968 | 198.50 |
| | Average | 16653 | 4.34 | 2.88 | 0.32 | 0.38 | 2.75 | 249.8 |

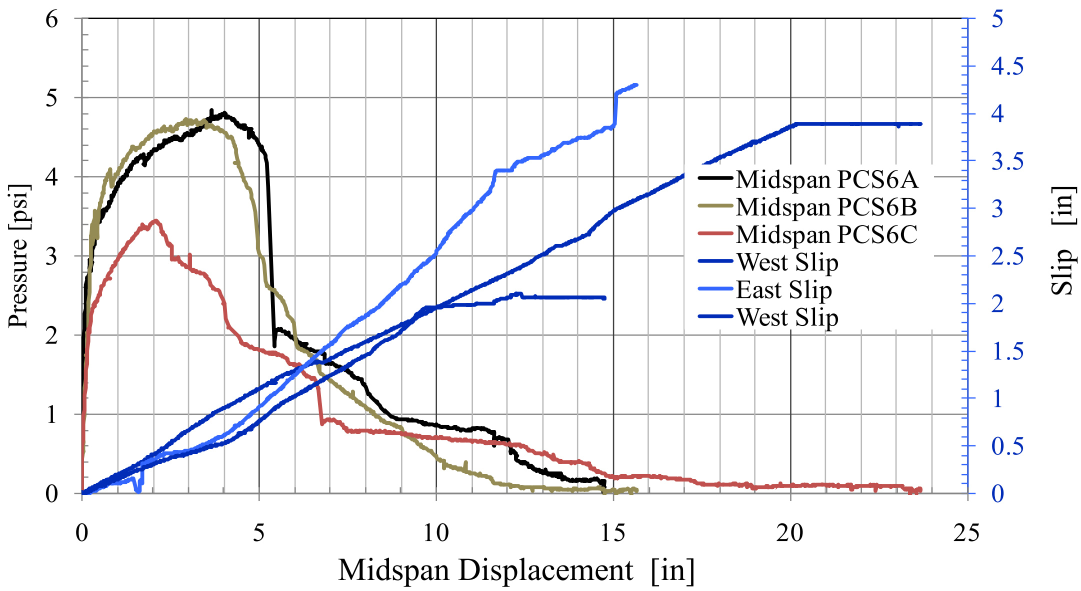


**Figure 103. PCS6 Pressure–Displacement Response**

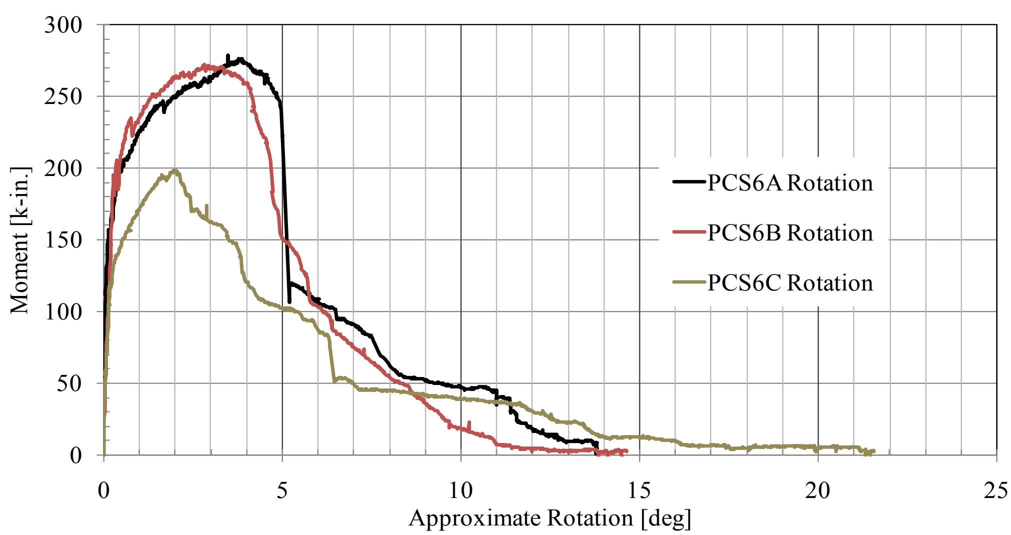


**Figure 104. PCS6 Moment–Rotation Response**


Distribution Statement A: Approved for public release; distribution unlimited.

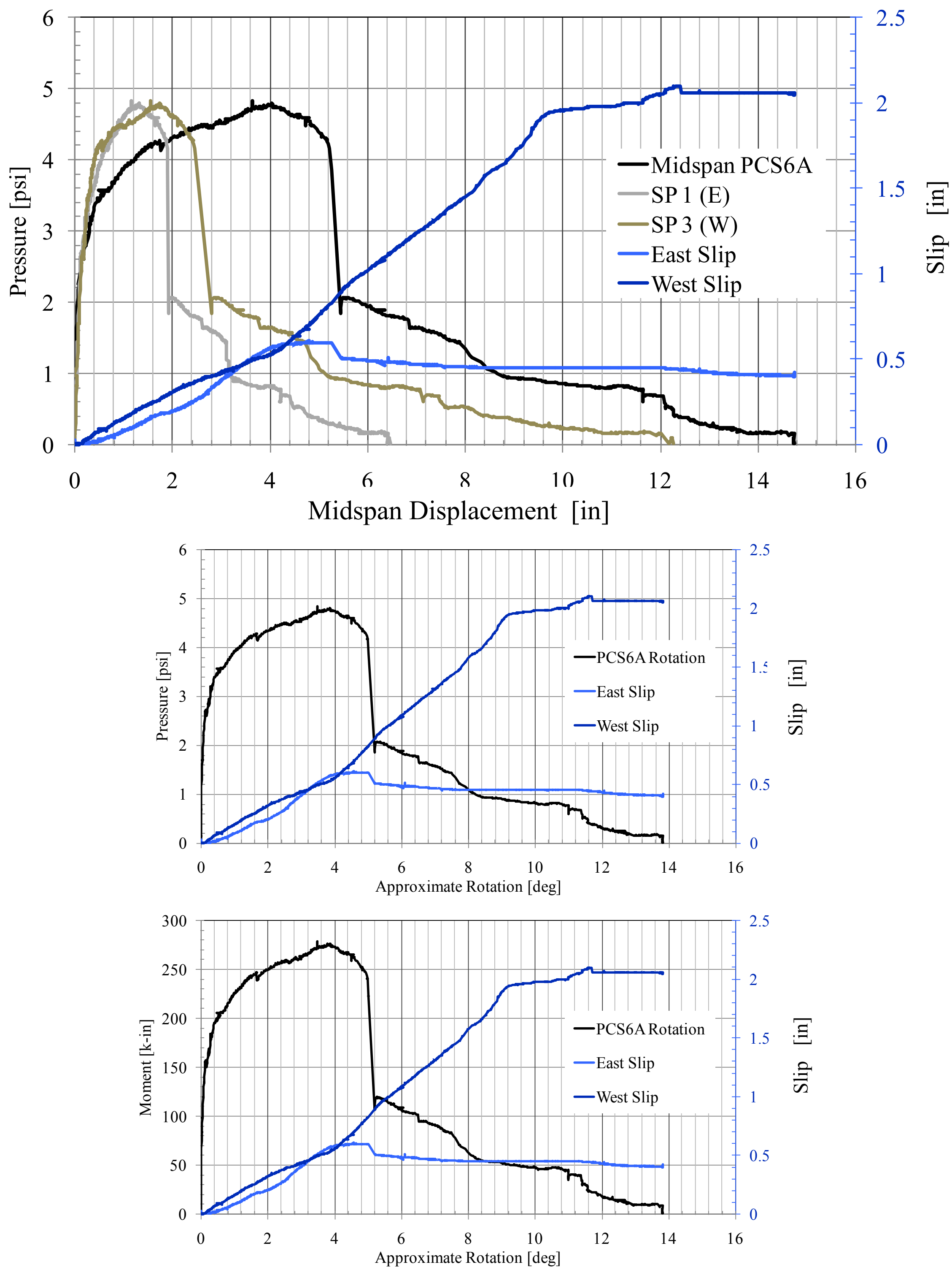


**Figure 105. PCS6-A Response**


Distribution Statement A: Approved for public release; distribution unlimited.

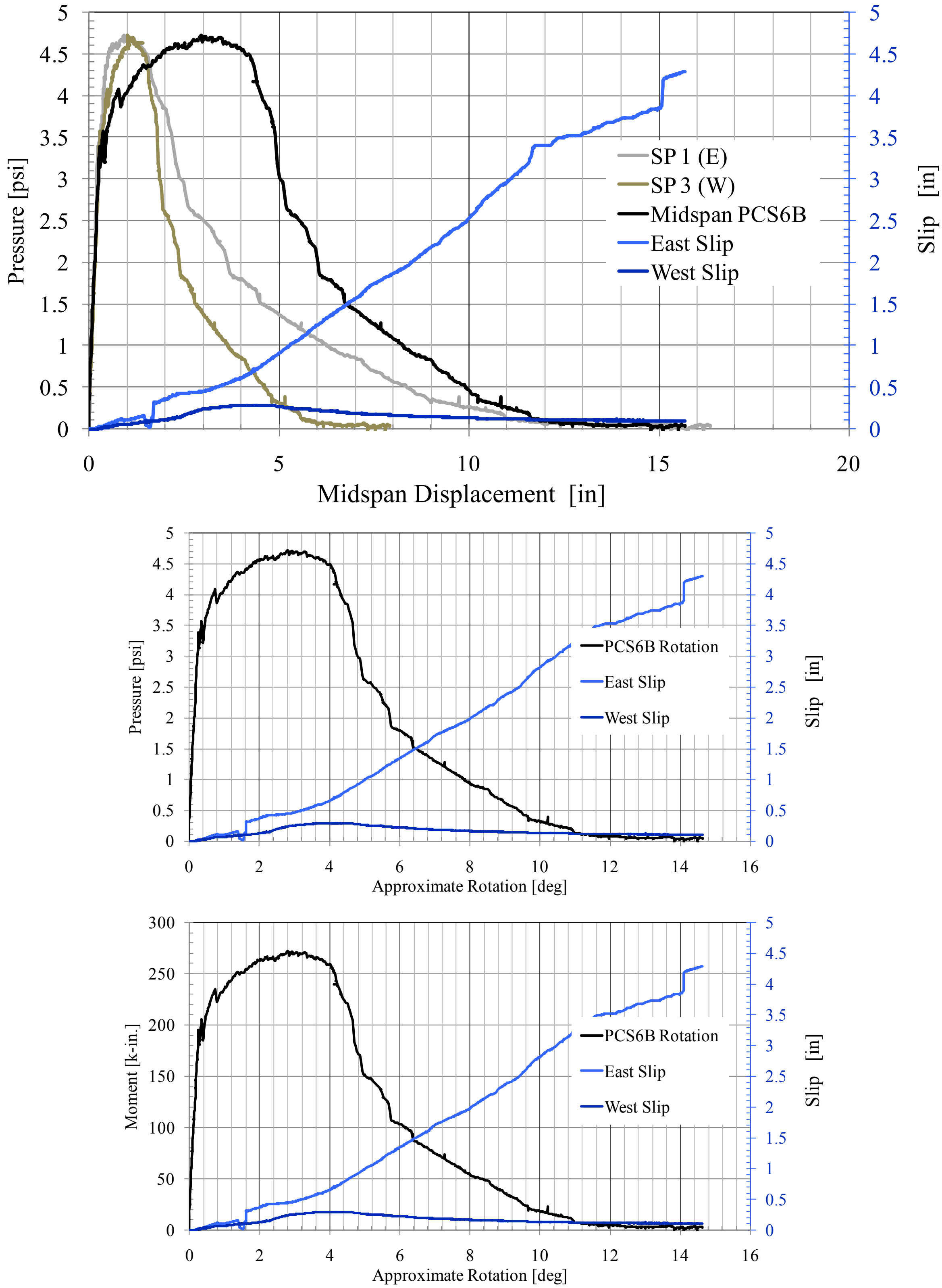


**Figure 106. PCS6-B Response**



Distribution Statement A: Approved for public release; distribution unlimited.

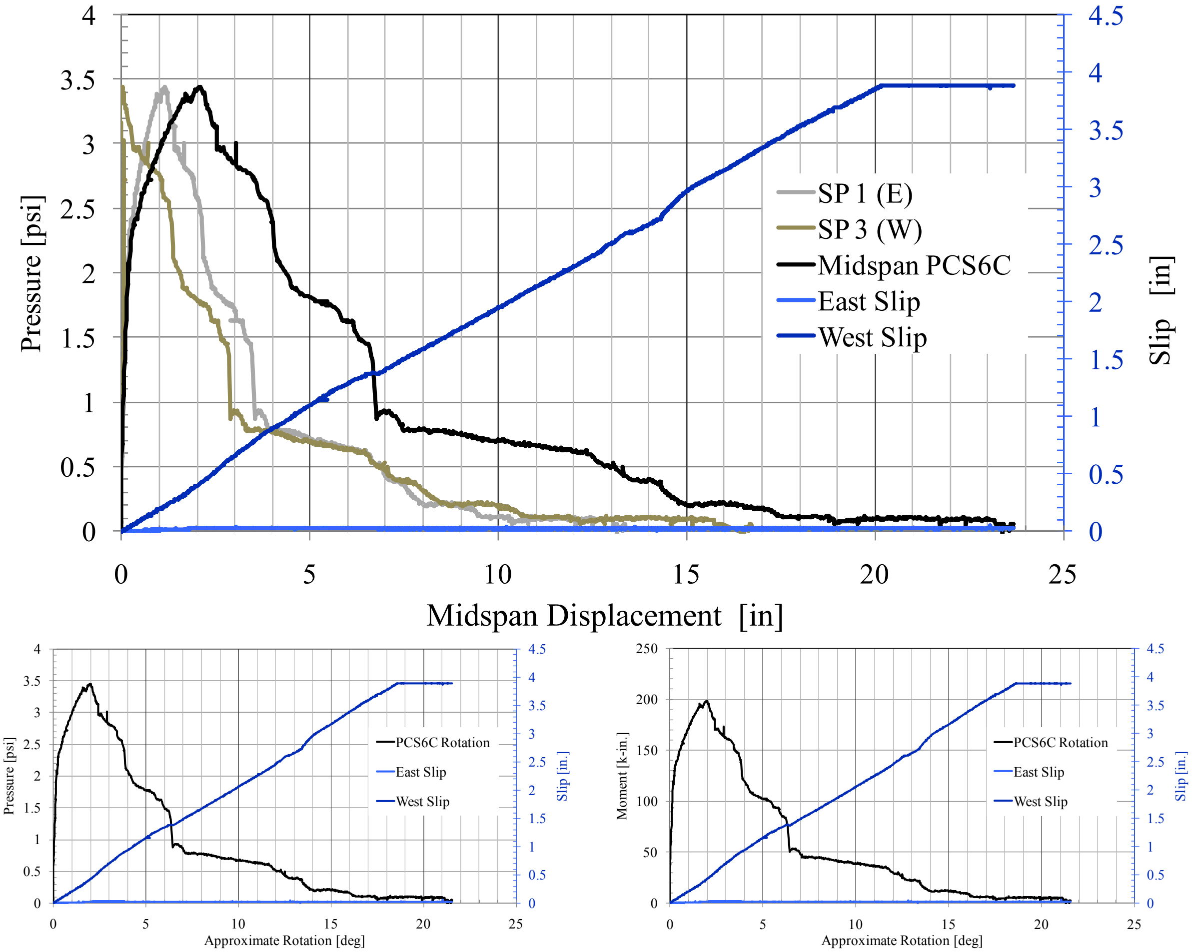


**Figure 107. PCS6-C Response**

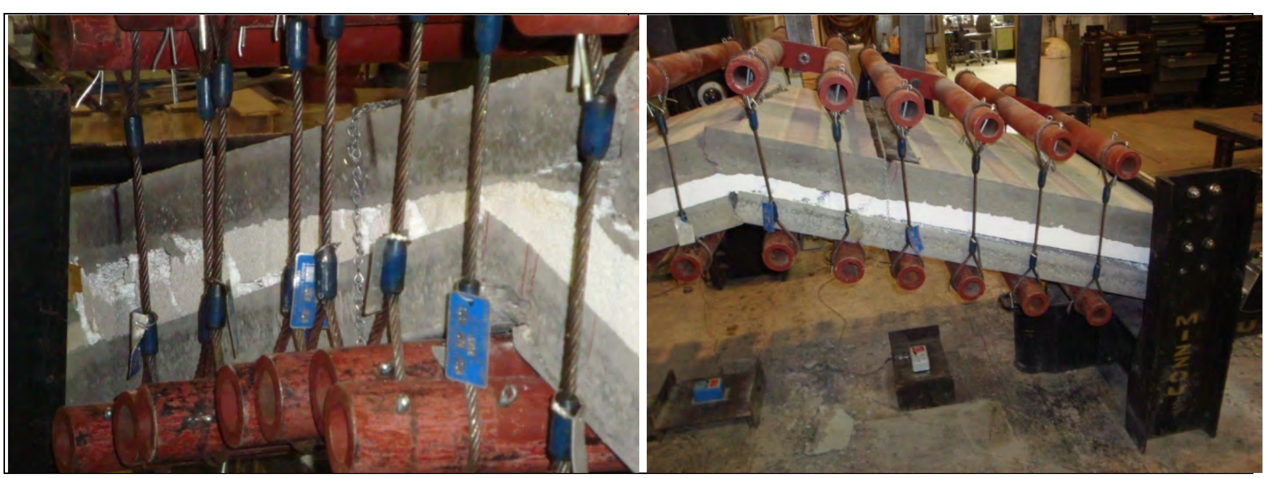

**Figure 108. PCS6 Panel Response (A, B)**



Distribution Statement A: Approved for public release; distribution unlimited.

## 6.10. PCS7 3-3-3 Specimen Performance

PCS7 consists of a partially composite 3-3-3 PC CSW panel fabricated with XPS insulation and glass fiber THERMOMASS® composite shear pins. The panel is conventionally reinforced with non-PS longitudinal bars and #3 transverse reinforcement in both the interior and exterior wythe. The panel cross-section and reinforcement details are illustrated in Figures 109 and 110.

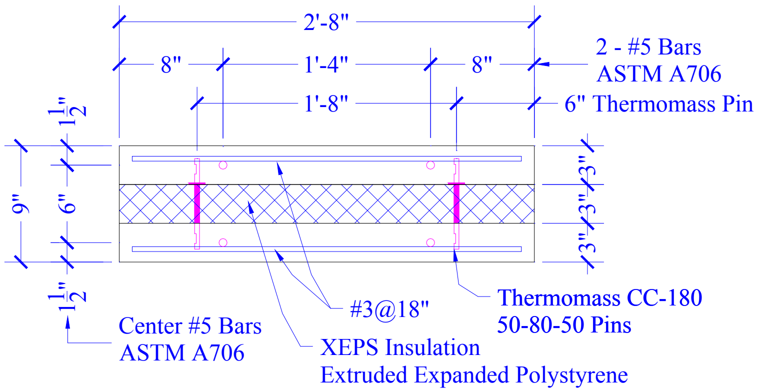


**Figure 109. PCS7 Cross-Section Detail**

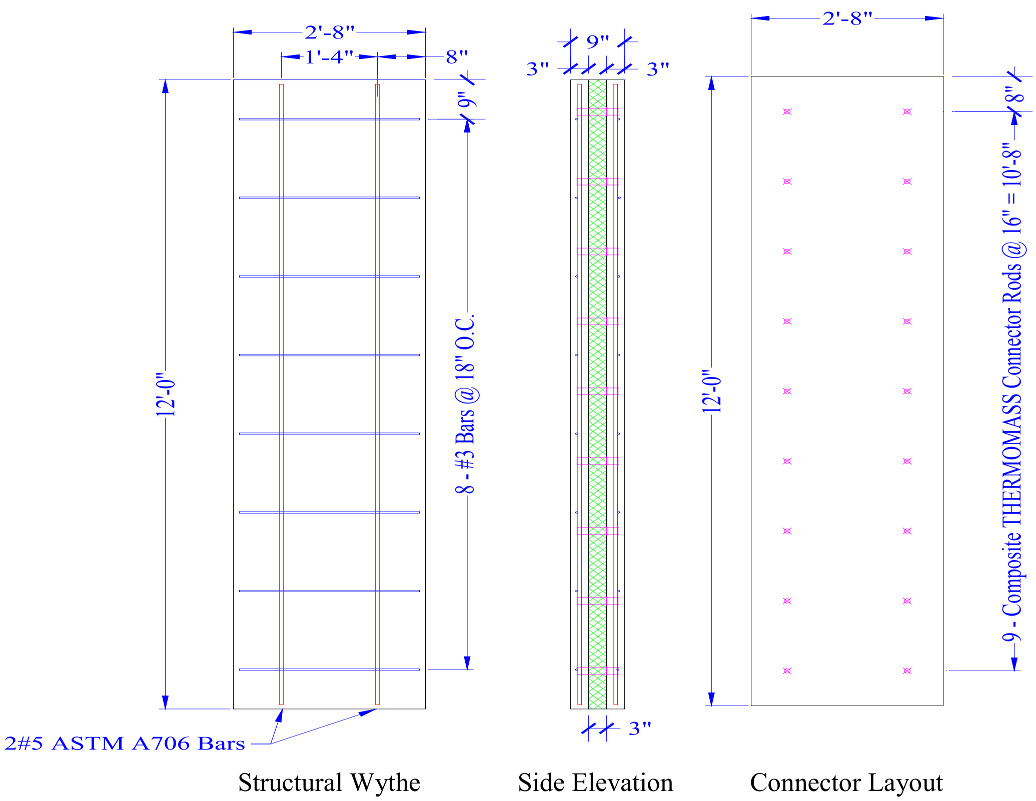


**Figure 110. PCS7 Panel Detail**



Distribution Statement A: Approved for public release; distribution unlimited.

The measured response is summarized in Table 26. The midspan pressure displacement and moment-support rotation for the three specimen are in Figures 111 and 112. The individual response of each panel and the end slip and quarter point displacements are included in Figures 113-115. Figure 116 shows a picture representation of the samples post-test.

**Table 26. PCS7 Measured Response**

| Specimen | Age at Test [days] | Max Load [lbs] | Max Pressure [psi] | Corresponding Displacement [in] | East Slip [in] | West Slip [in] | Rot. [deg] | Measured Moment Capacity [k-in] |
|---|---|---|---|---|---|---|---|---|
| PCS7-A | 106 | 18661 | 4.860 | 7.434 | 0.847 | 0.809 | 7.063 | 279.91 |
| PCS7-B | 106 | 19484 | 5.074 | 6.744 | 0.615 | 0.905 | 6.413 | 292.26 |
| PCS7-C | 94 | 15561 | 4.0524 | 4.4584 | 0.2757 | 0.7599 | 4.2497 | 233.42 |
| | Average | 17902 | 4.66 | 6.21 | 0.58 | 0.82 | 5.91 | 268.5 |

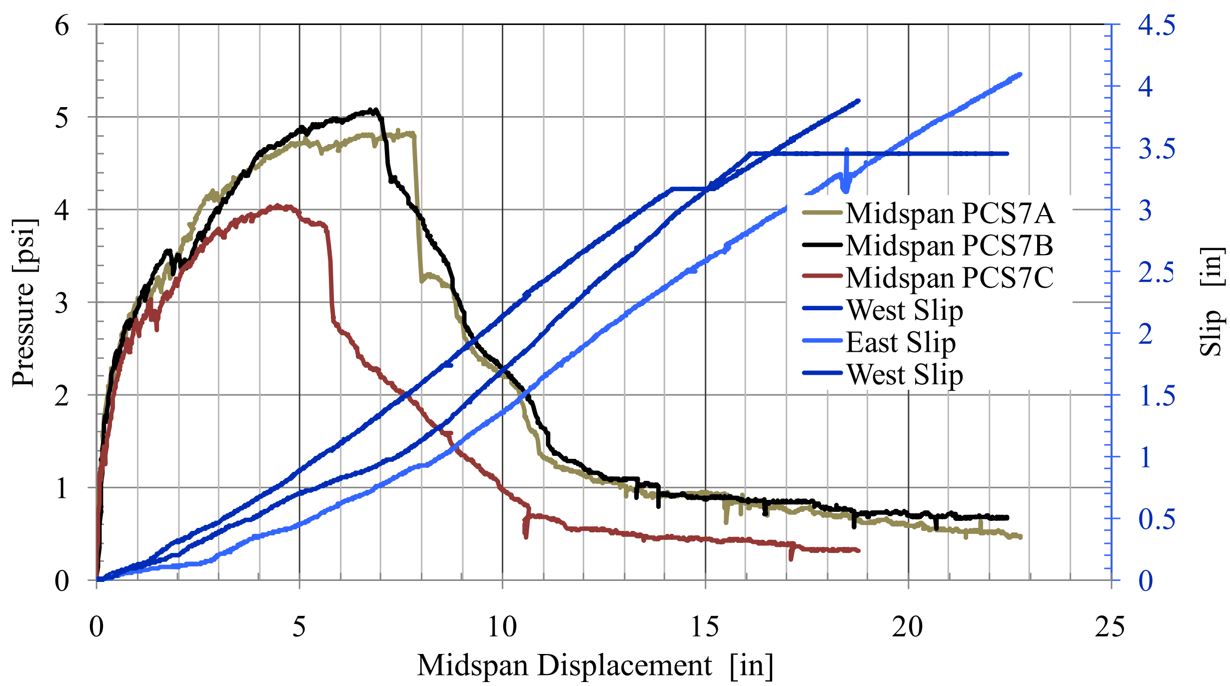


**Figure 111. PCS7 Pressure–Displacement Response**



Distribution Statement A: Approved for public release; distribution unlimited.

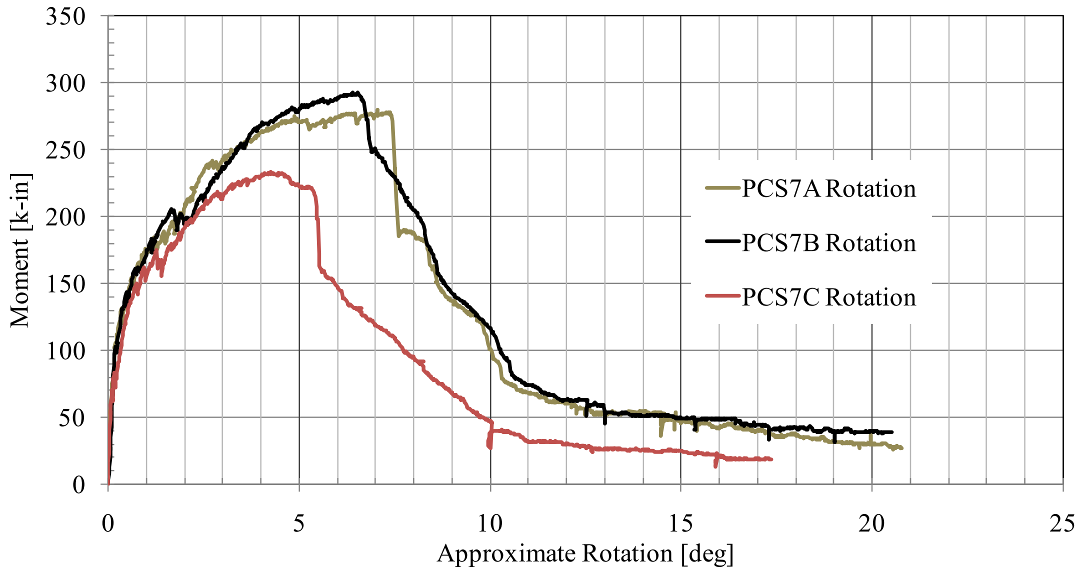


**Figure 112. PCS7 Moment–Rotation Response**

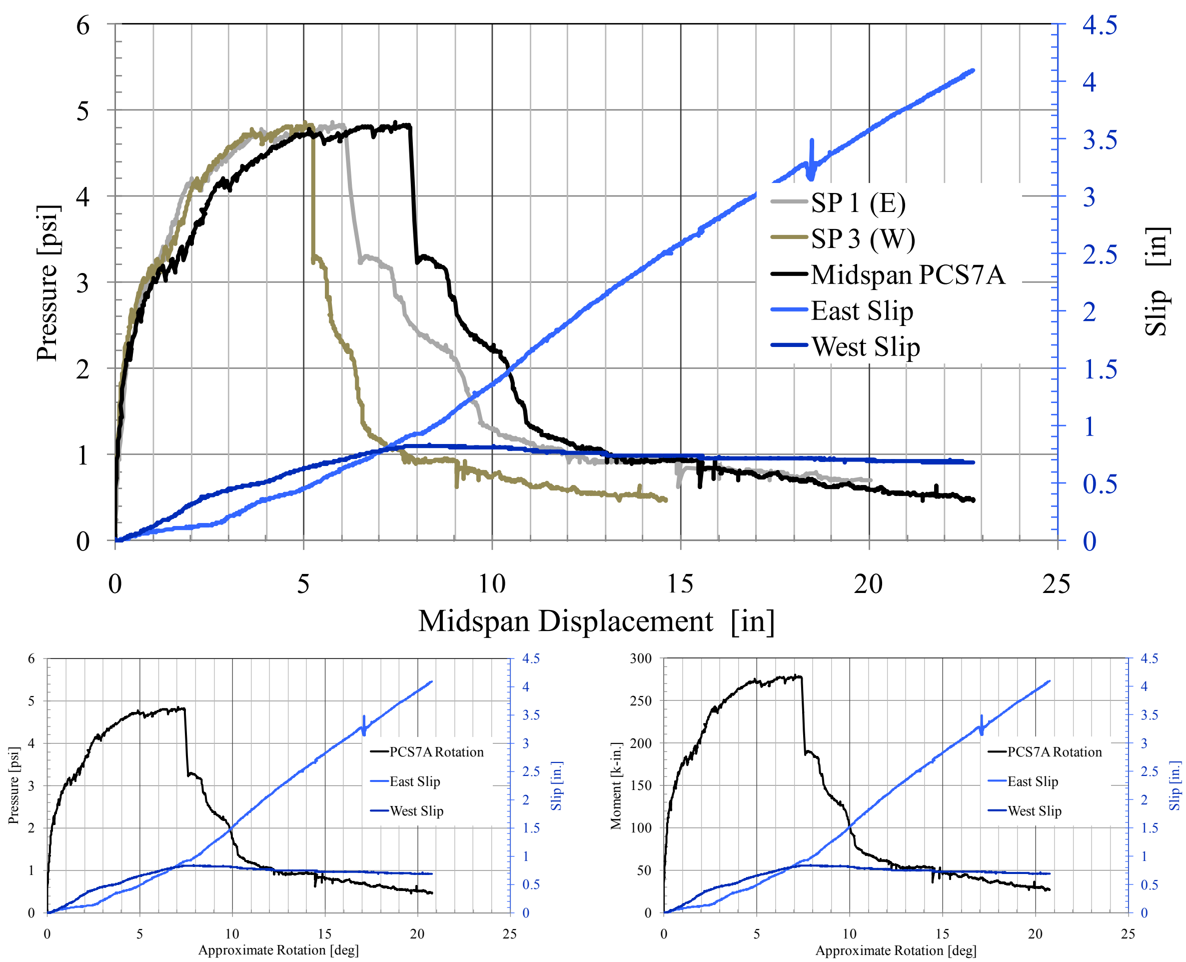


**Figure 113. PCS7-A Response**



Distribution Statement A: Approved for public release; distribution unlimited.

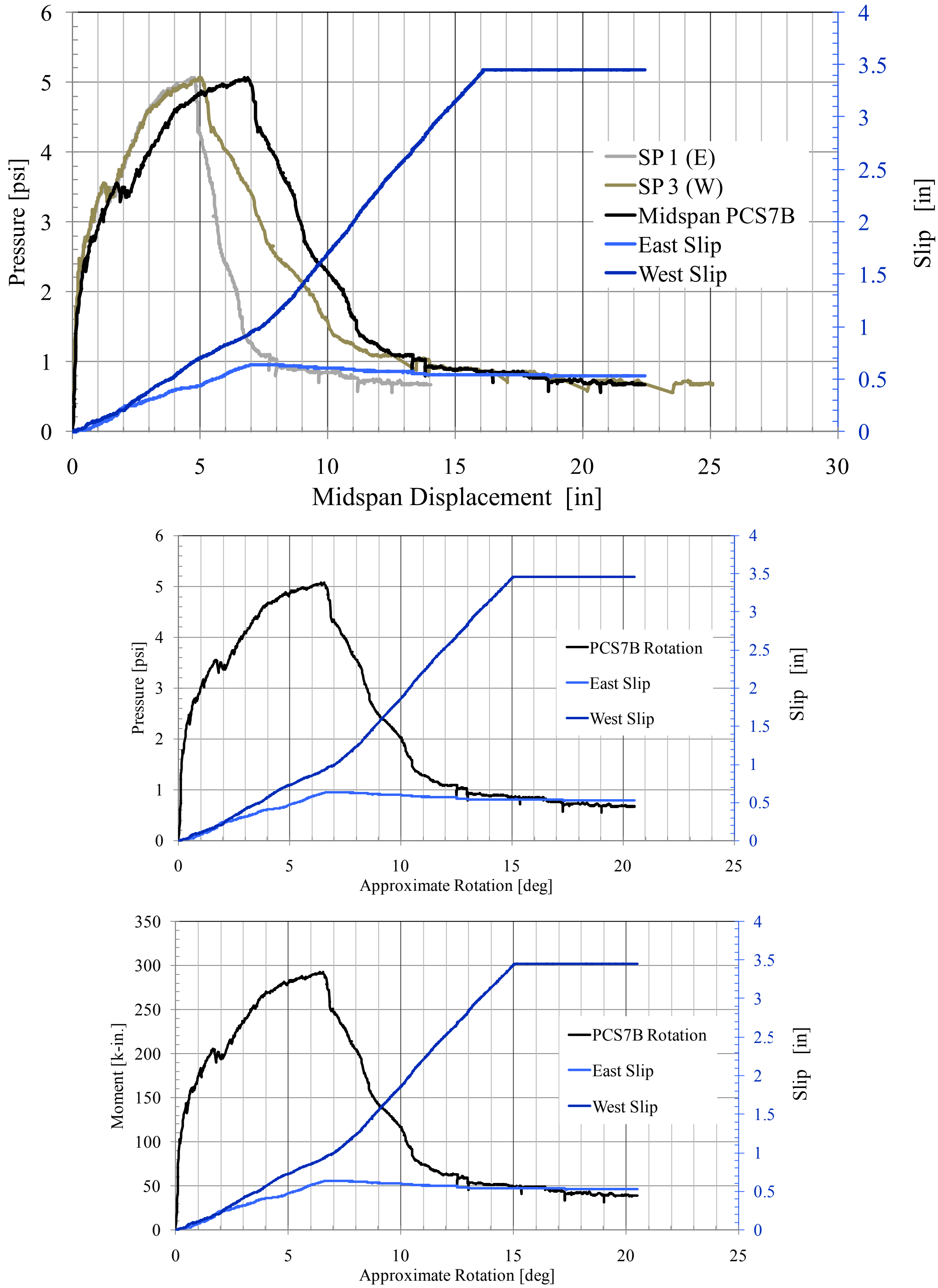


**Figure 114. PCS7-B Response**



Distribution Statement A: Approved for public release; distribution unlimited.

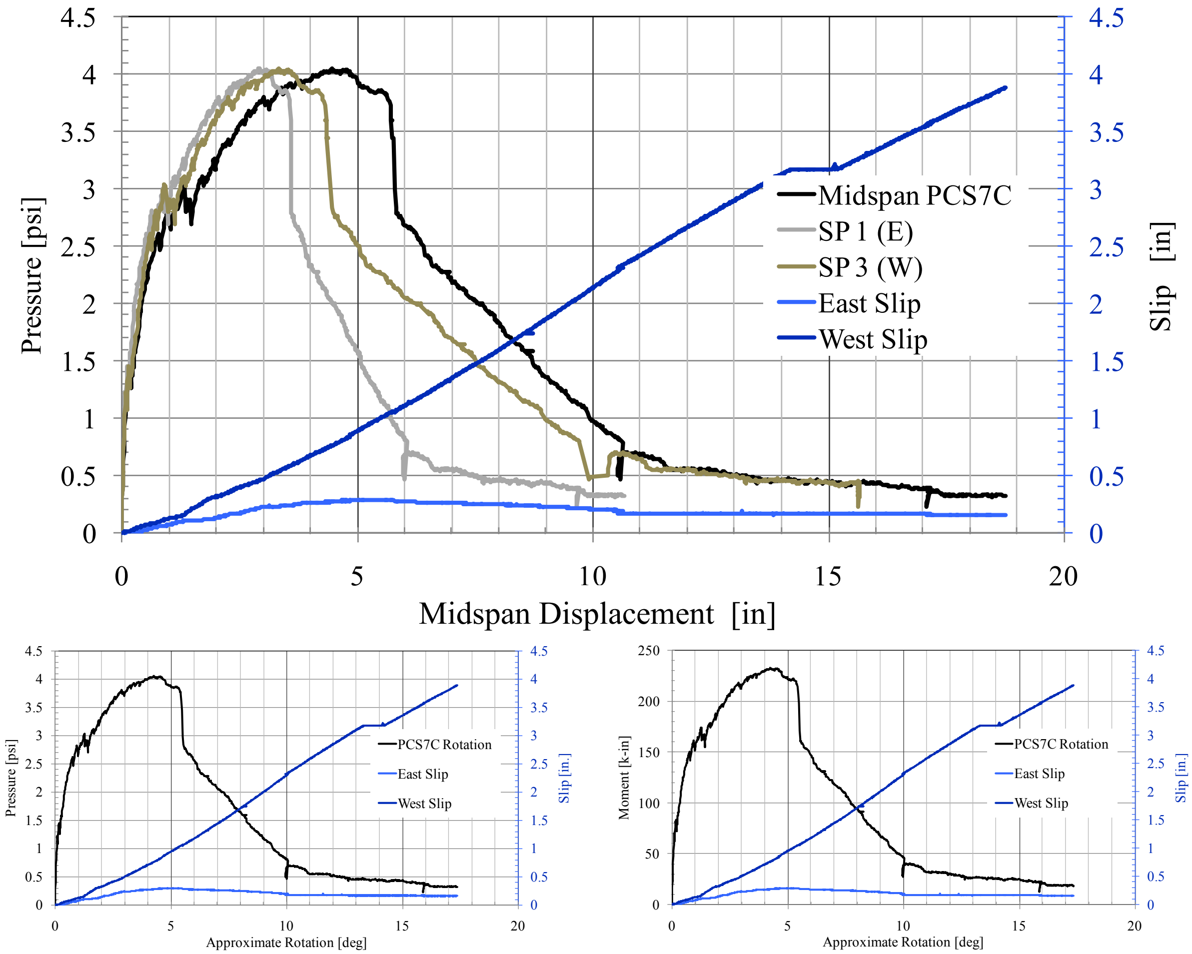


**Figure 115. PCS7-C Response**

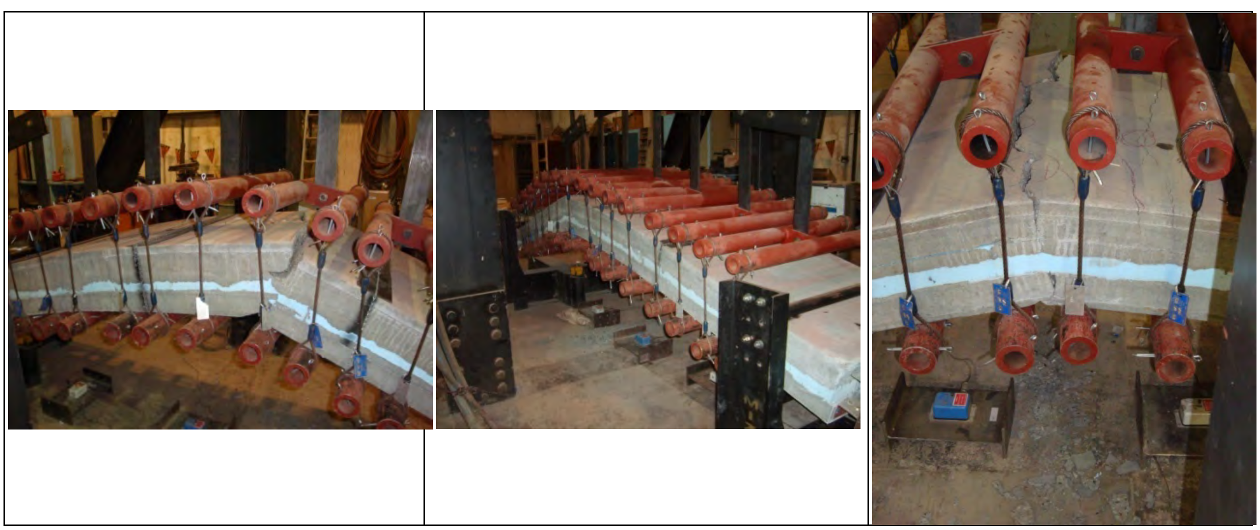

**Figure 116. PCS7 Panel Response (A, B, C)**



Distribution Statement A: Approved for public release; distribution unlimited.

### 6.11. PCS8 3-3-3 Specimen Performance

PCS8 consists of a partially composite 3-3-3 PC CSW panel fabricated with PIMA insulation and glass fiber THERMOMASS® composite shear pins. The panel is PS with rebar transverse reinforcement in both the interior and exterior wythe. The panel cross-section and reinforcement details are illustrated in Figures 117 and 118.

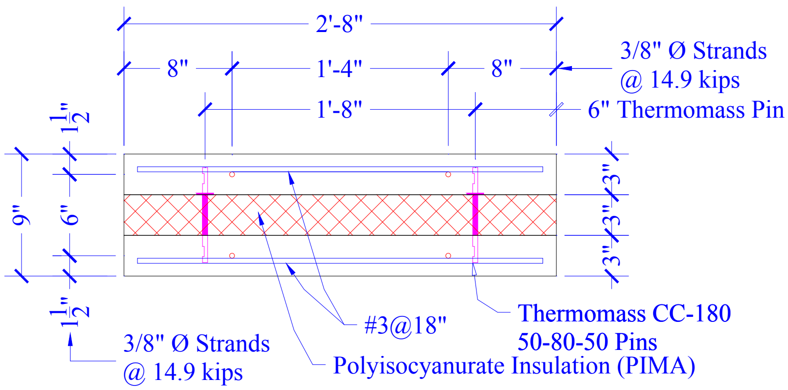


Figure 117. PCS8 Cross-Section Detail

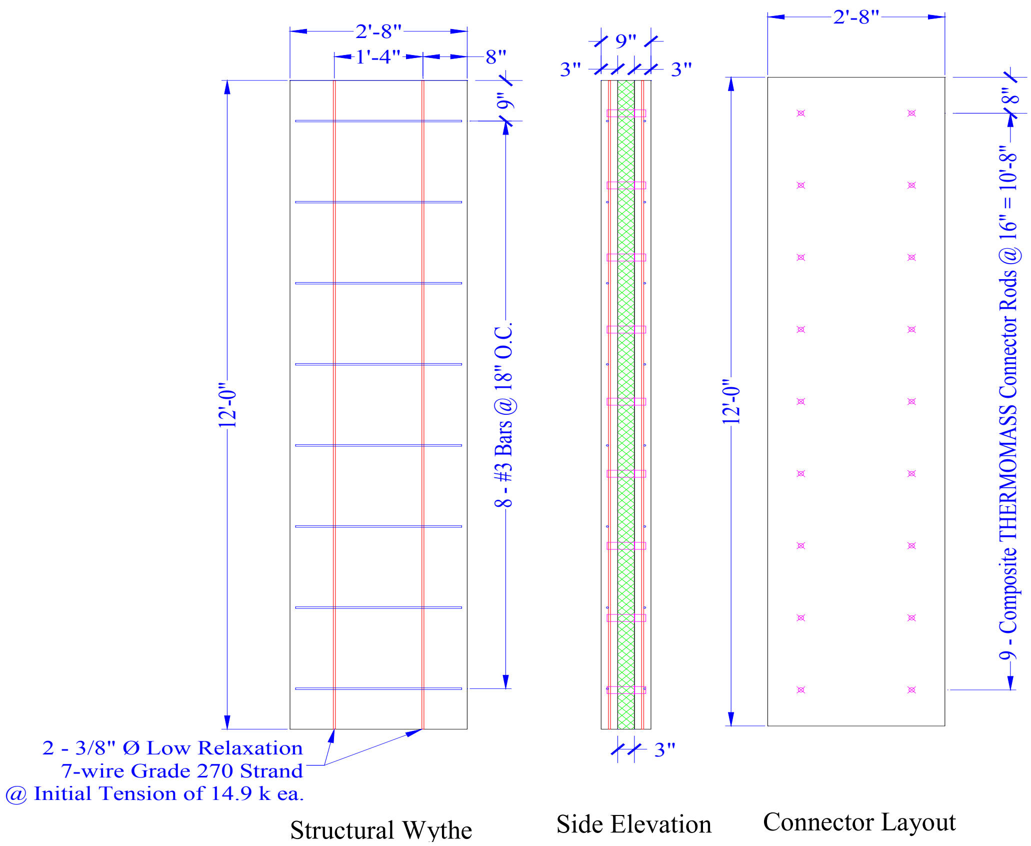


Figure 118. PCS8 Panel Detail



Distribution Statement A: Approved for public release; distribution unlimited.

The measured response is summarized in Table 27. The midspan pressure displacement and moment–support rotation for the three specimens are in Figures 119 and 120. The individual response of each panel and the end slip and quarter point displacements are included in Figures 121-123. Figure 124 shows a picture representation of the samples post-test.

Note: Due to a control problem during testing, PCS8-B was loaded very rapidly. The data acquisition was on; however, due to the slow acquisition rate only three data points were recorded. The data thus appear to be tri-linear. This is a consequence of the aforementioned testing issues and not variability in the panel performance.

**Table 27. PCS8 Measured Response**

| Specimen | Age at Test [days] | Max Load [lbs] | Max Pressure [psi] | Corresponding Displacement [in] | East Slip [in] | West Slip [in] | Rot. [deg] | Measured Moment Capacity [k-in] |
|---|---|---|---|---|---|---|---|---|
| PCS8-A | 101 | 15051 | 3.9195 | 4.3814 | 0.6930 | 0.3873 | 4.1765 | 225.76 |
| PCS8-B | 108 | 14369 | 3.7420 | 2.6614 | 0.5794 | 0.2102 | 2.5398 | 215.54 |
| PCS8-C | 108 | 16901 | 4.4013 | 5.2511 | 0.6607 | 0.5929 | 5.0017 | 253.51 |
| | Average | 15440 | 4.02 | 4.10 | 0.64 | 0.40 | 3.91 | 231.6 |

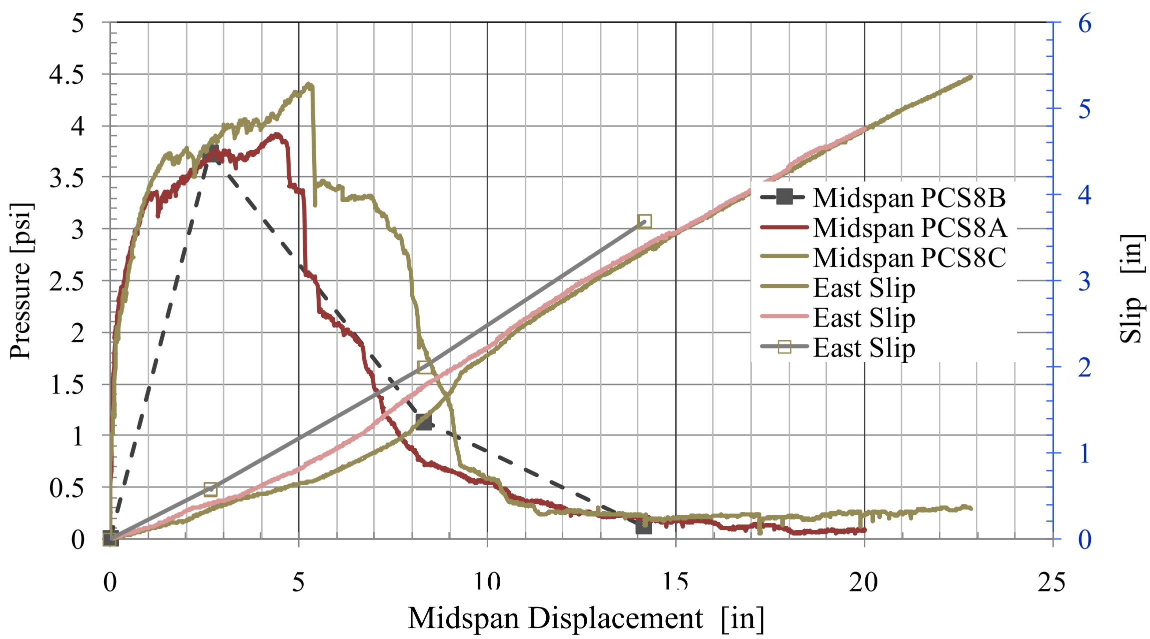


**Figure 119. PCS8 Pressure–Displacement Response**



Distribution Statement A: Approved for public release; distribution unlimited.

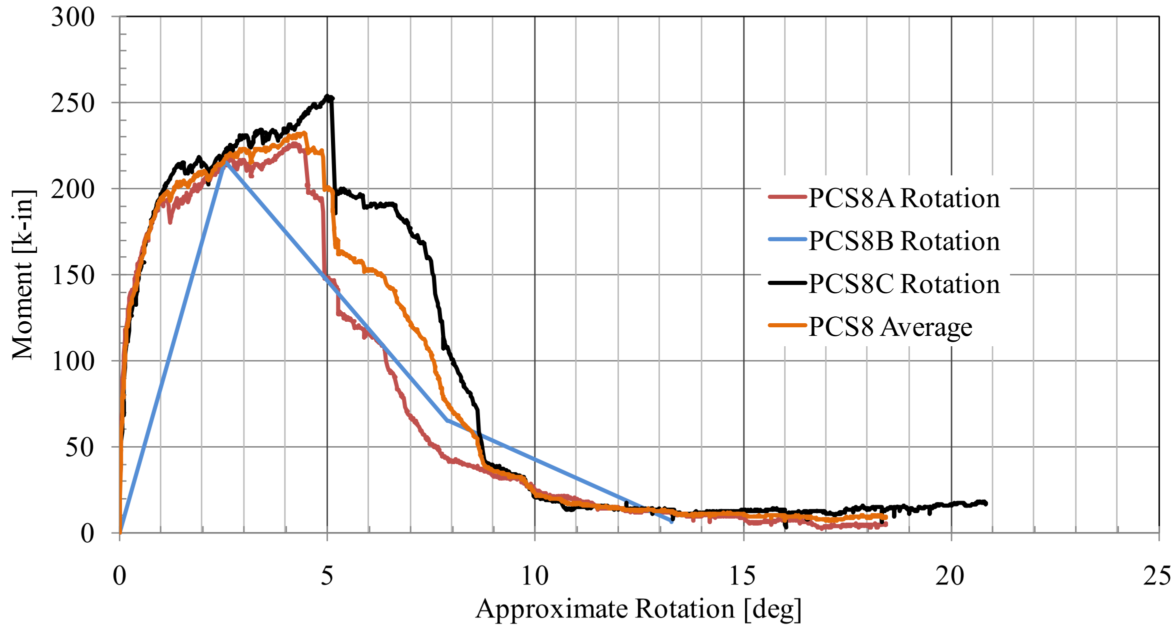


**Figure 120. PCS8 Moment–Rotation Response**

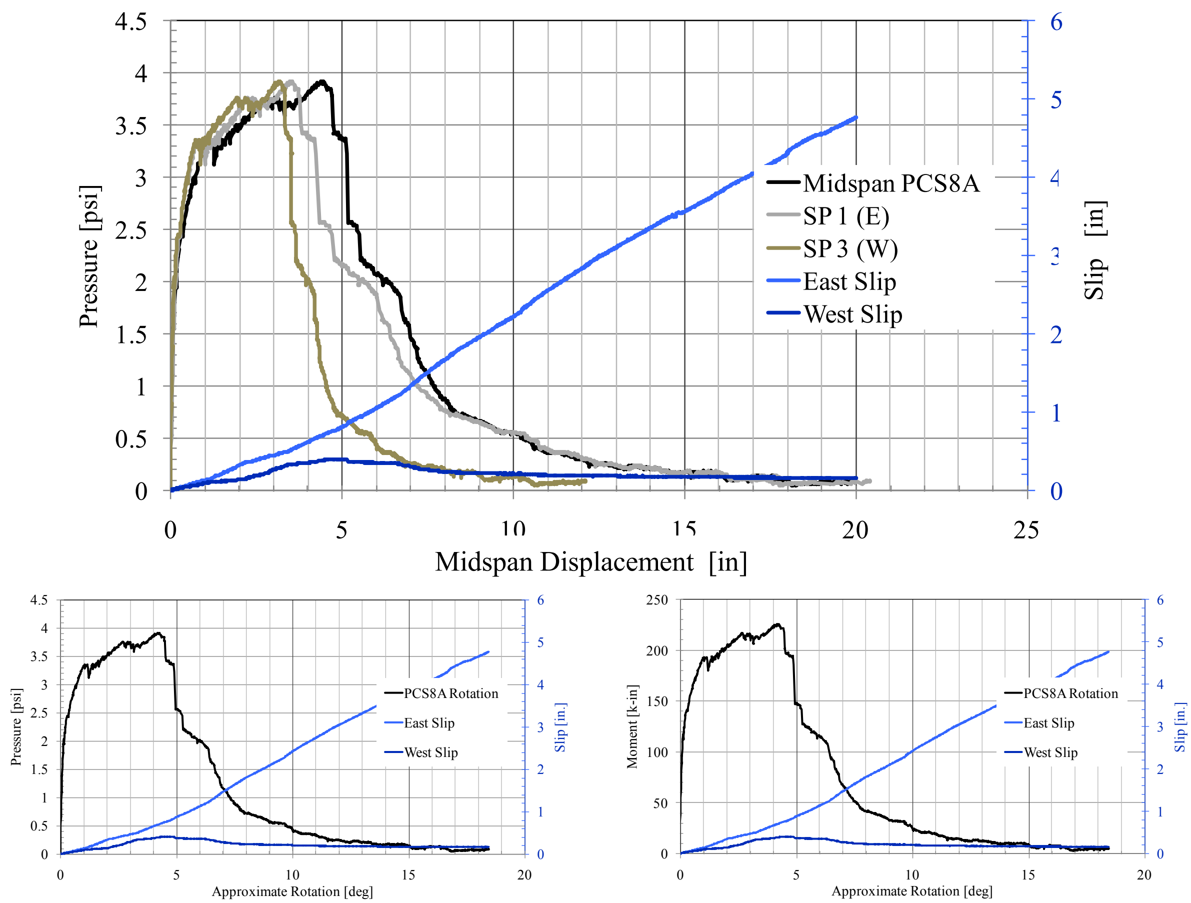


**Figure 121. PCS8-A Response**



Distribution Statement A: Approved for public release; distribution unlimited.

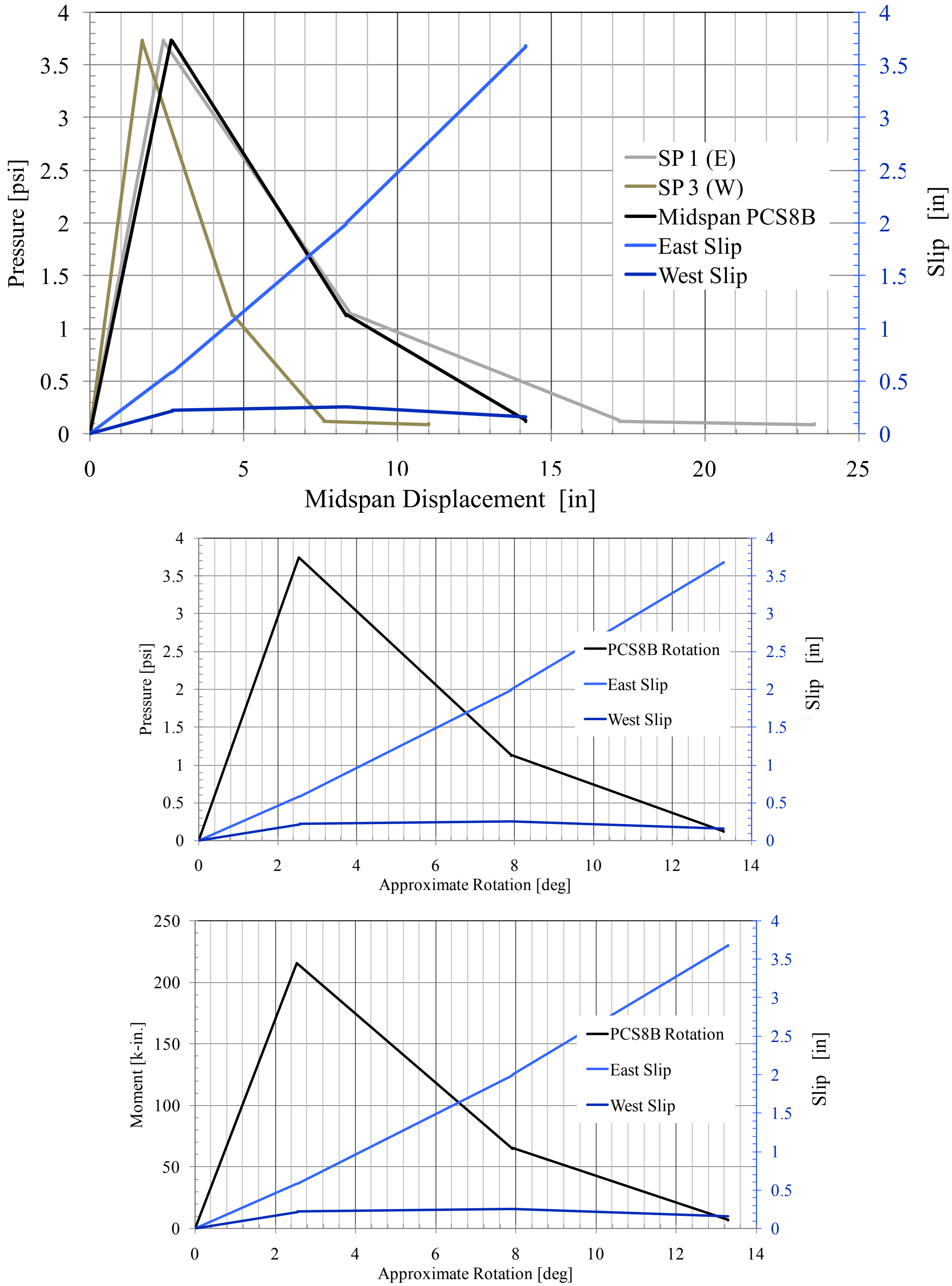


**Figure 122. PCS8-B Response**



Distribution Statement A: Approved for public release; distribution unlimited.

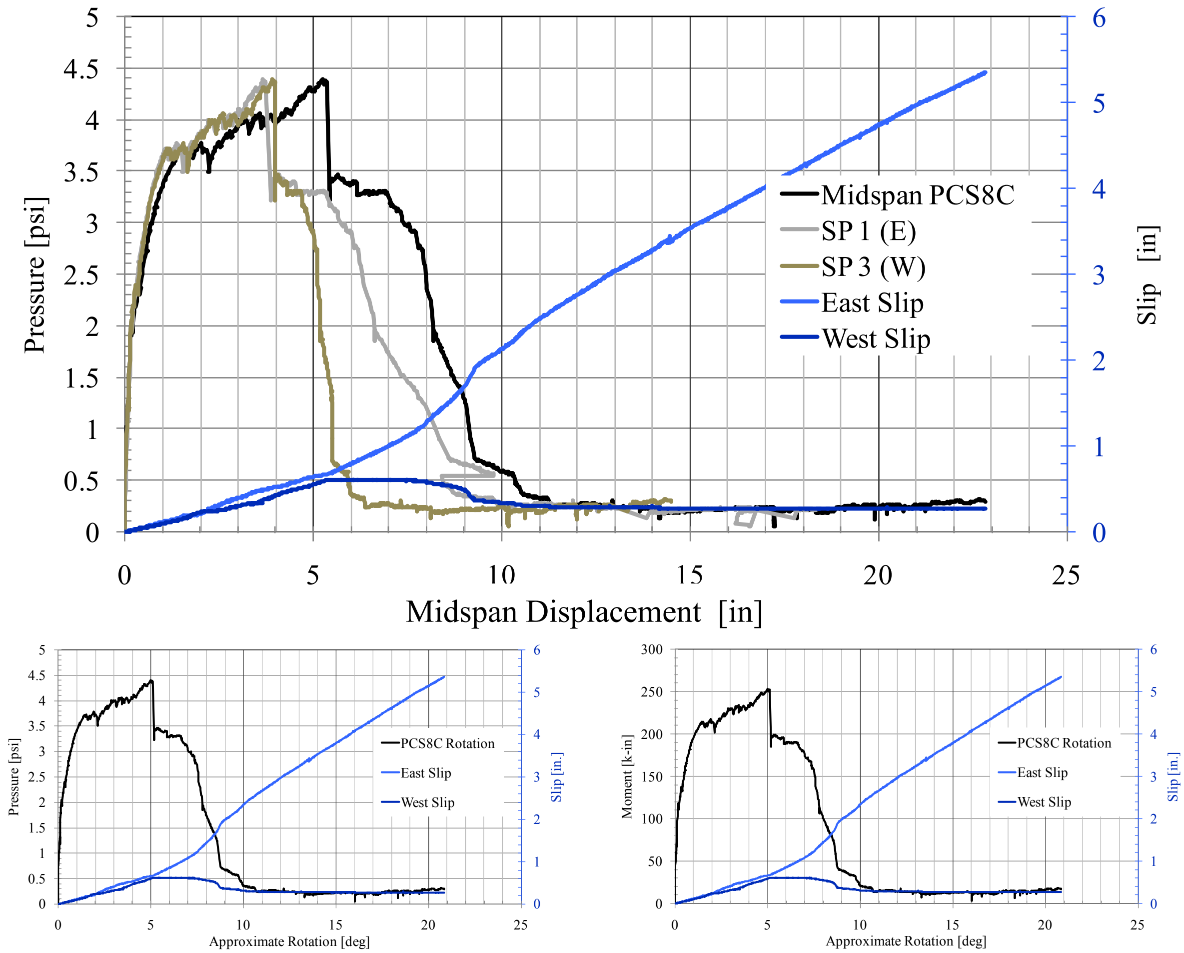


**Figure 123. PCS8-C Response**

**Figure 124. PCS8 Panel Response (A and C)**


Distribution Statement A: Approved for public release; distribution unlimited.

## 6.12. PCS9 3-3-3 Specimen Performance

PCS9 consists of a partially composite 3-3-3 PC CSW panel fabricated with PIMA insulation and carbon fiber C-Grid® shear pins. The panel is prestressed with WWR transverse reinforcement in both the interior and exterior wythe. The panel cross-section and reinforcement details are illustrated in Figures 125 and 126.

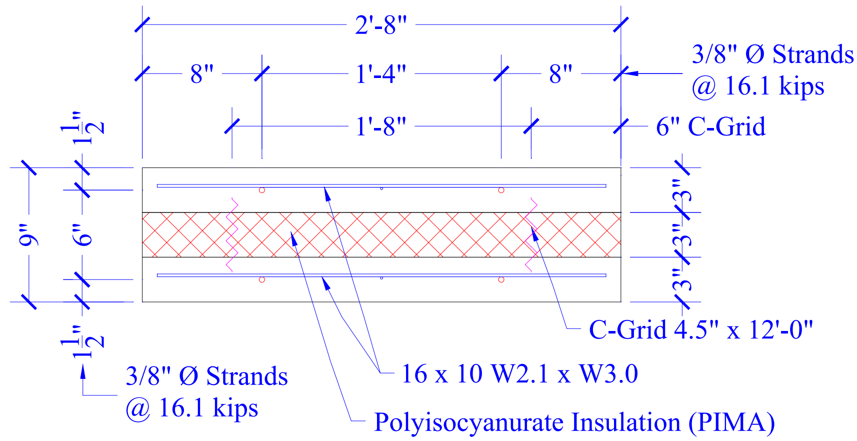


**Figure 125. PCS9 Cross-Section Detail**

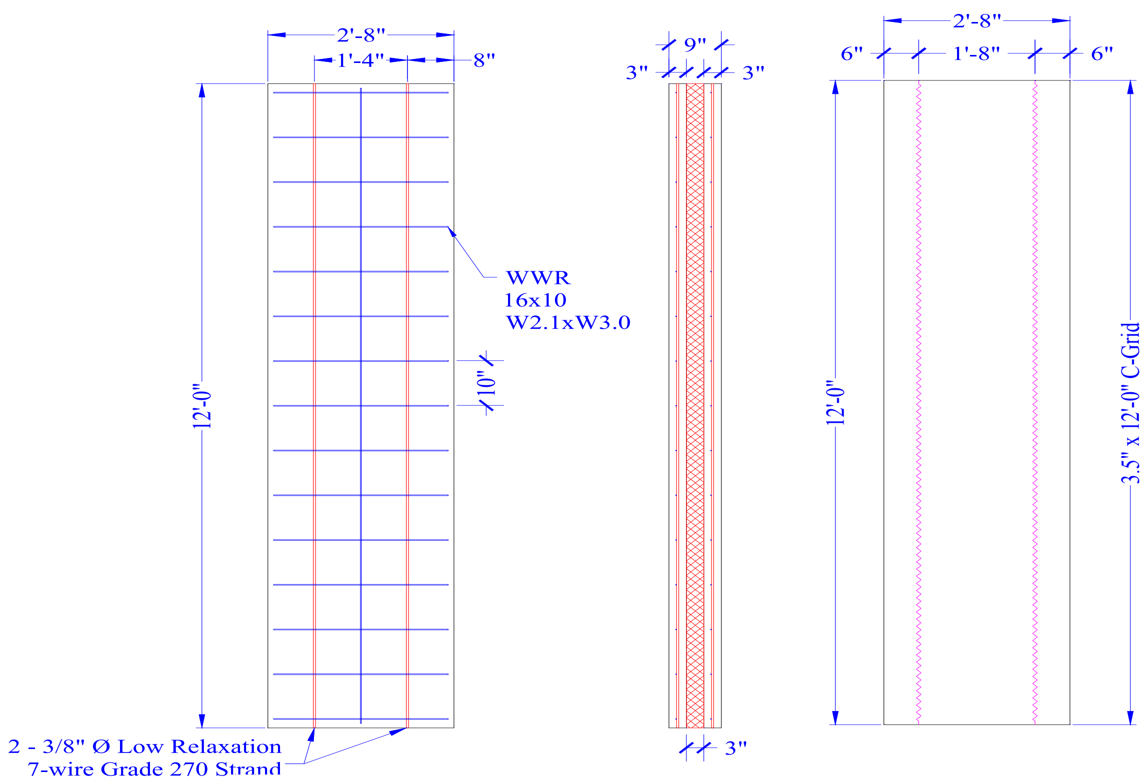


**Figure 126. PCS9 Panel Detail**


Distribution Statement A: Approved for public release; distribution unlimited.

The measured response is summarized in Table 28. The midspan pressure displacement and moment–support rotation for the three specimen are in Figures 127 and 128. The individual response of each panel and the end slip and quarter point displacements are included in Figures 129-131. Figure 132 shows a picture representation of the samples post-test.

**Table 28. PCS9 Measured Response**

| Specimen | Age at Test [days] | Max Load [lbs] | Max Pressure [psi] | Corresponding Displacement [in] | East Slip [in] | West Slip [in] | Rot. [deg] | Measured Moment Capacity [k-in] |
|---|---|---|---|---|---|---|---|---|
| PCS9-A | 37 | 21311 | 5.550 | 1.809 | 0.190 | 0.180 | 1.727 | 319.67 |
| PCS9-B | 41 | 20804 | 5.418 | 1.882 | 0.235 | 0.133 | 1.797 | 312.06 |
| PCS9-C | 41 | 22455 | 5.848 | 2.573 | 0.152 | 0.356 | 2.456 | 336.82 |
| | Average | 21524 | 5.61 | 2.09 | 0.19 | 0.22 | 1.99 | 322.9 |

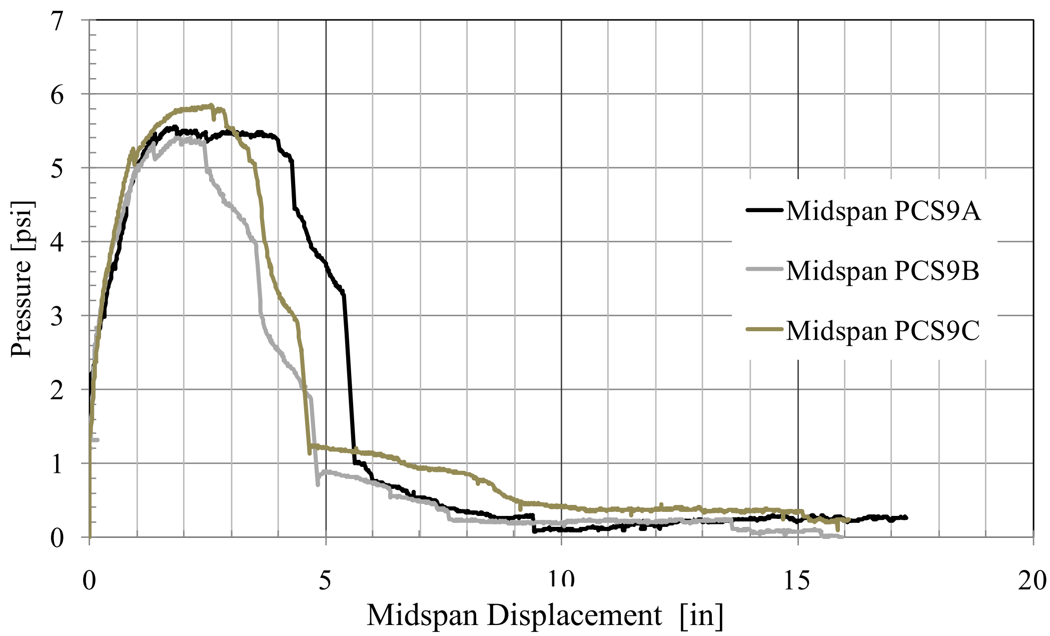


**Figure 127. PCS9 Pressure–Displacement Response**



Distribution Statement A: Approved for public release; distribution unlimited.

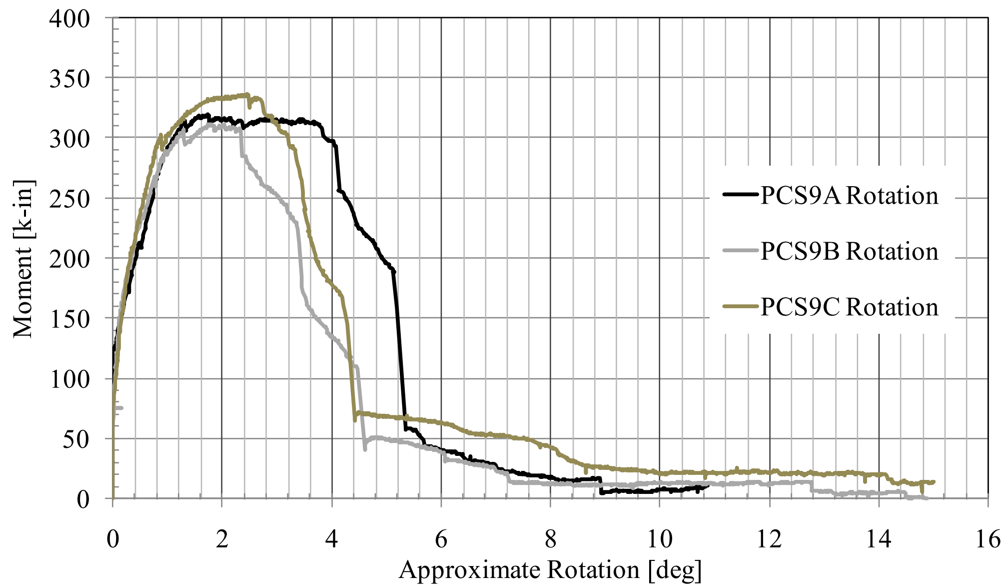


**Figure 128. PCS9 Moment–Rotation Response**

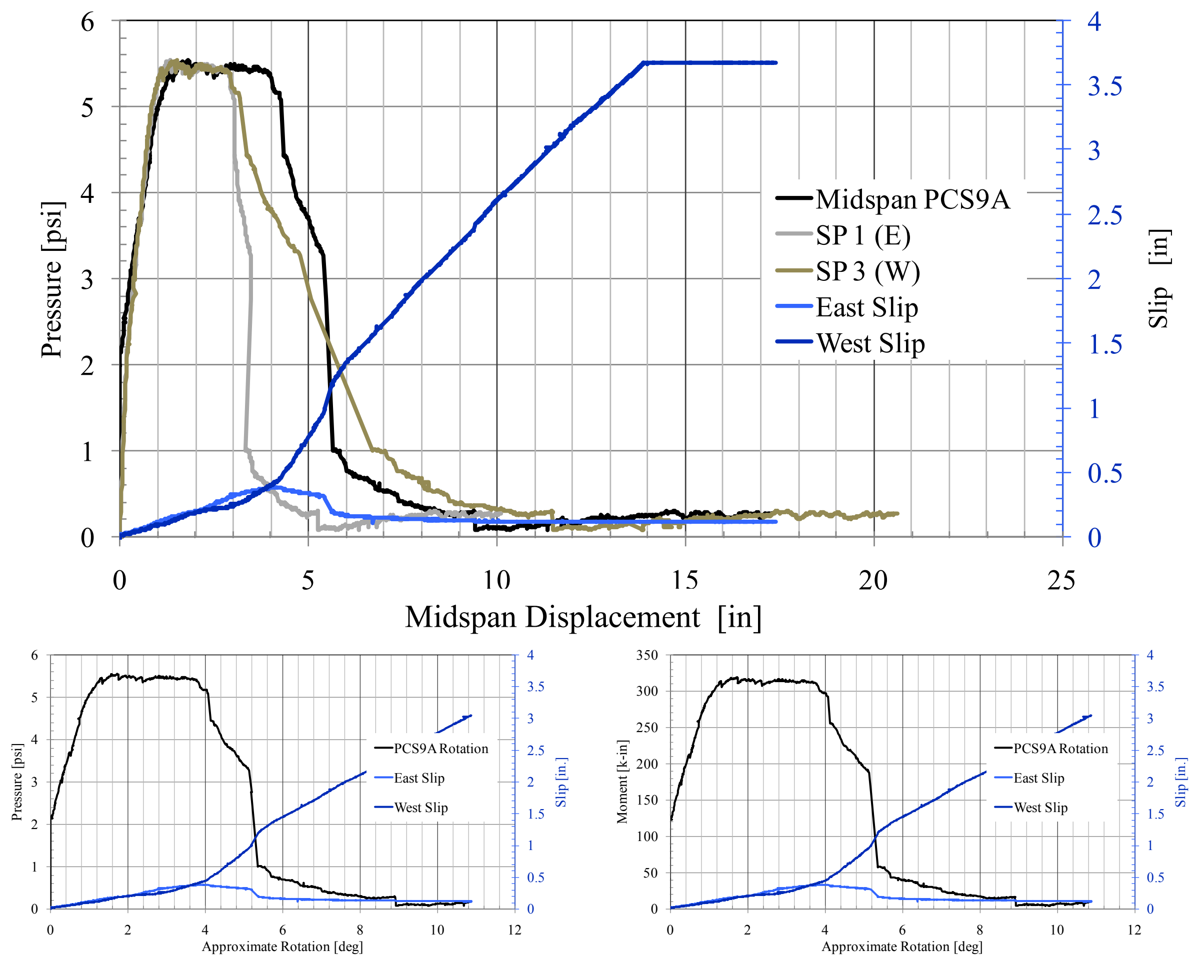


**Figure 129. PCS9-A Response**



Distribution Statement A: Approved for public release; distribution unlimited.

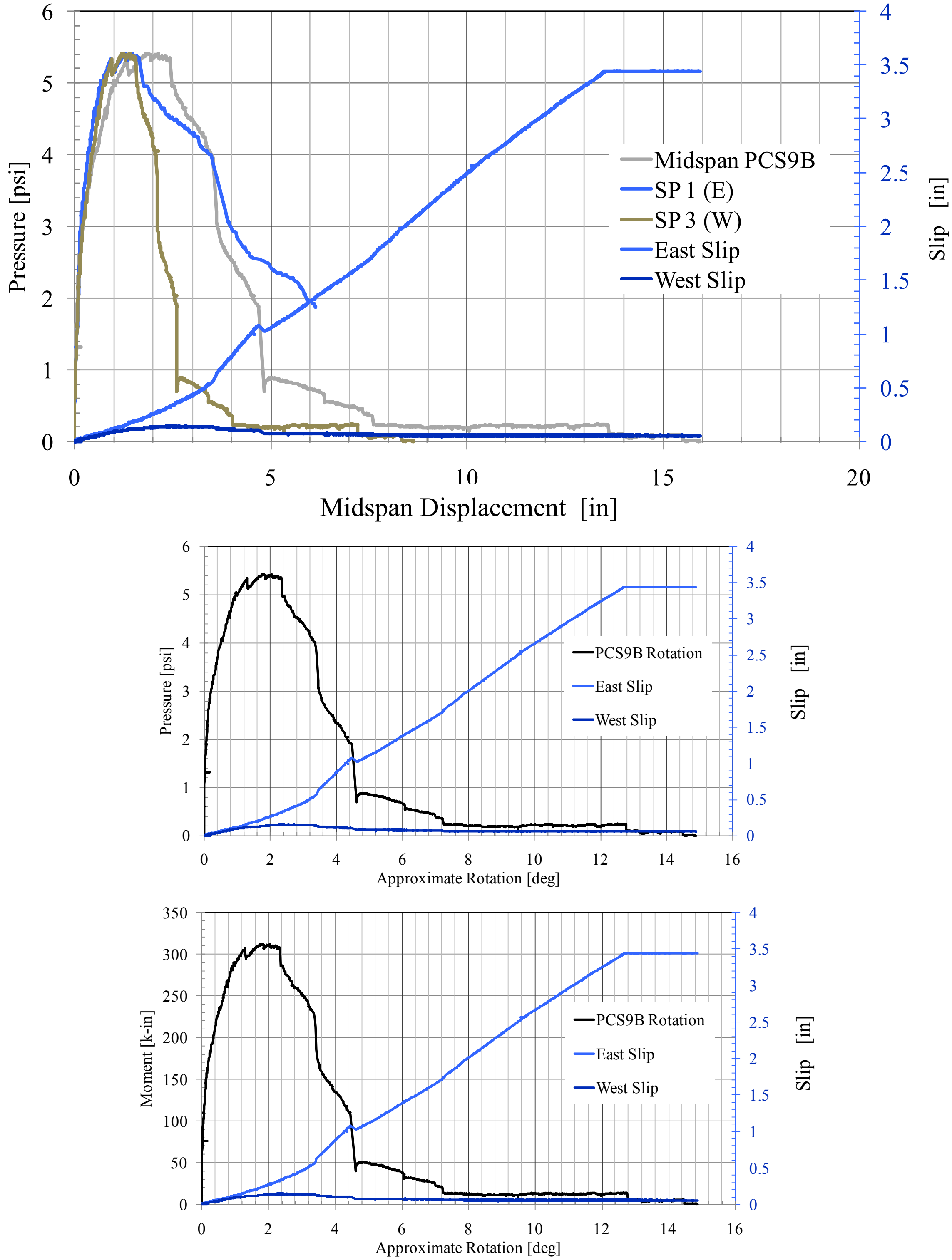


**Figure 130. PCS9-B Response**



Distribution Statement A: Approved for public release; distribution unlimited.

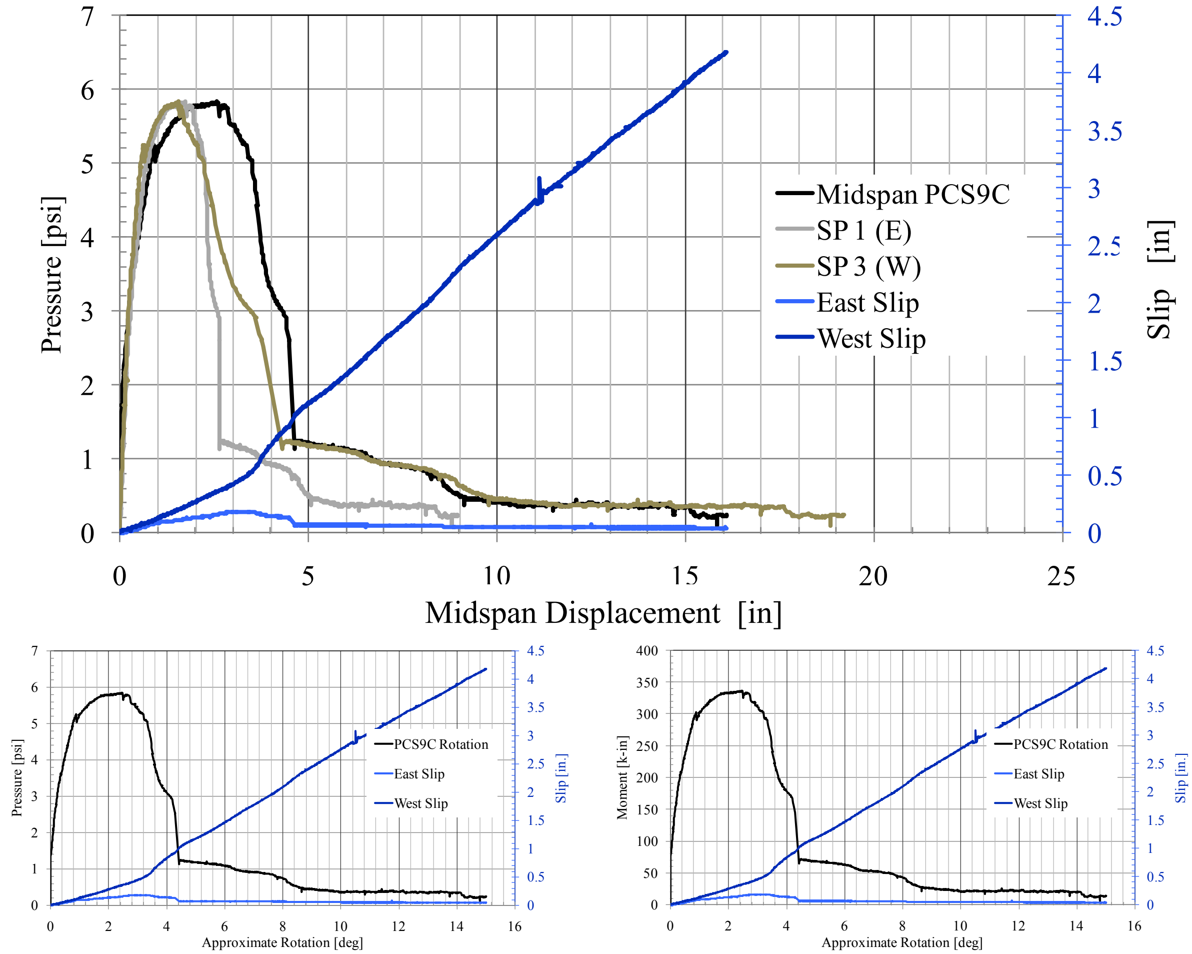


**Figure 131. PCS9-C Response**

**Figure 132. PCS9 Panel Response (A, B, C)**

## 6.13. Tin1 3-4-3 Specimen Performance (Bonded Strand)

Tin1 consists of a partially composite 3-4-3 PC CSW panel fabricated with XPS insulation and Meadow Burke steel truss girder shear ties. The panel is prestressed with conventional transverse reinforcement in both the interior and exterior wythe. The panel cross-section and reinforcement details are illustrated in Figures 133 and 134.


Distribution Statement A: Approved for public release; distribution unlimited.

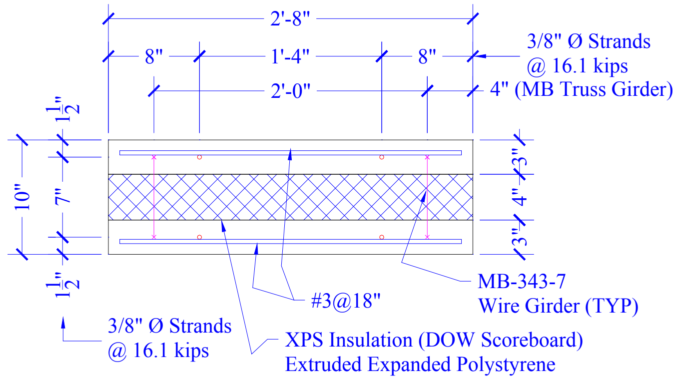


**Figure 133. Tin1 Cross-Section Detail**

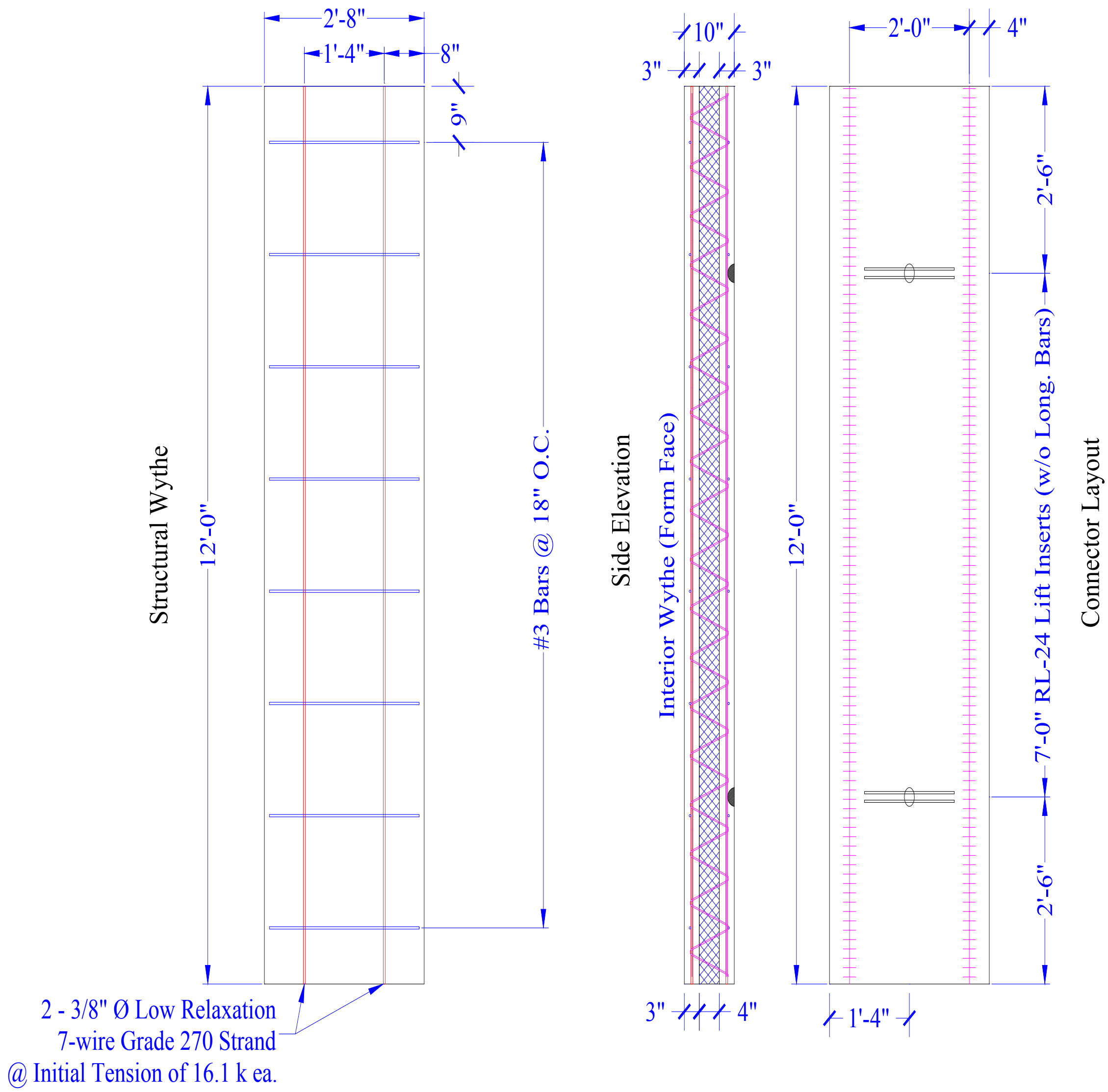


**Figure 134. Tin1 Panel Detail**


Distribution Statement A: Approved for public release; distribution unlimited.

The measured response is summarized in Table 29. The midspan pressure displacement for the three specimen are in Figure 135. The individual response of each panel and the quarter point displacements are included in Figure 136, Figure 137 and Figure 138.

**Table 29. Tin1 Measured Response**

| Specimen | Age at Test [days] | Max Load [lbs] | Max Pressure [psi] | Corresponding Displacement [in] | East Slip [in] | West Slip [in] | Rot. [deg] | Measured Moment Capacity [k-in] |
|---|---|---|---|---|---|---|---|---|
| Tin1-A | 95 | 21867 | 5.69 | 0.47 | NA | NA | 0.446 | 328.0 |
| Tin1-B | 99 | 20331 | 5.29 | 0.58 | NA | NA | 0.553 | 305.0 |
| Tin1-C | 204 | 20044 | 5.22 | 0.71 | NA | NA | 0.681 | 300.7 |
| | | 20747 | 5.40 | 0.59 | NA | NA | 0.56 | 311.2 |

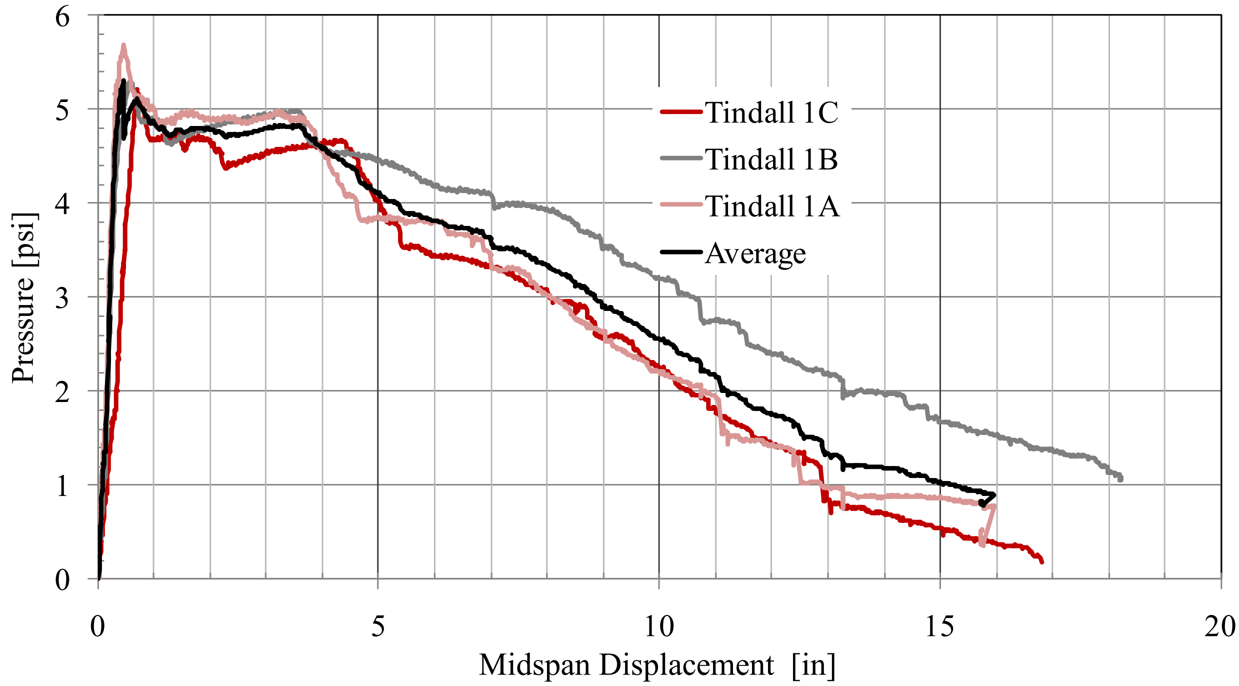


**Figure 135. Tin1 Pressure–Displacement Response**


Distribution Statement A: Approved for public release; distribution unlimited.

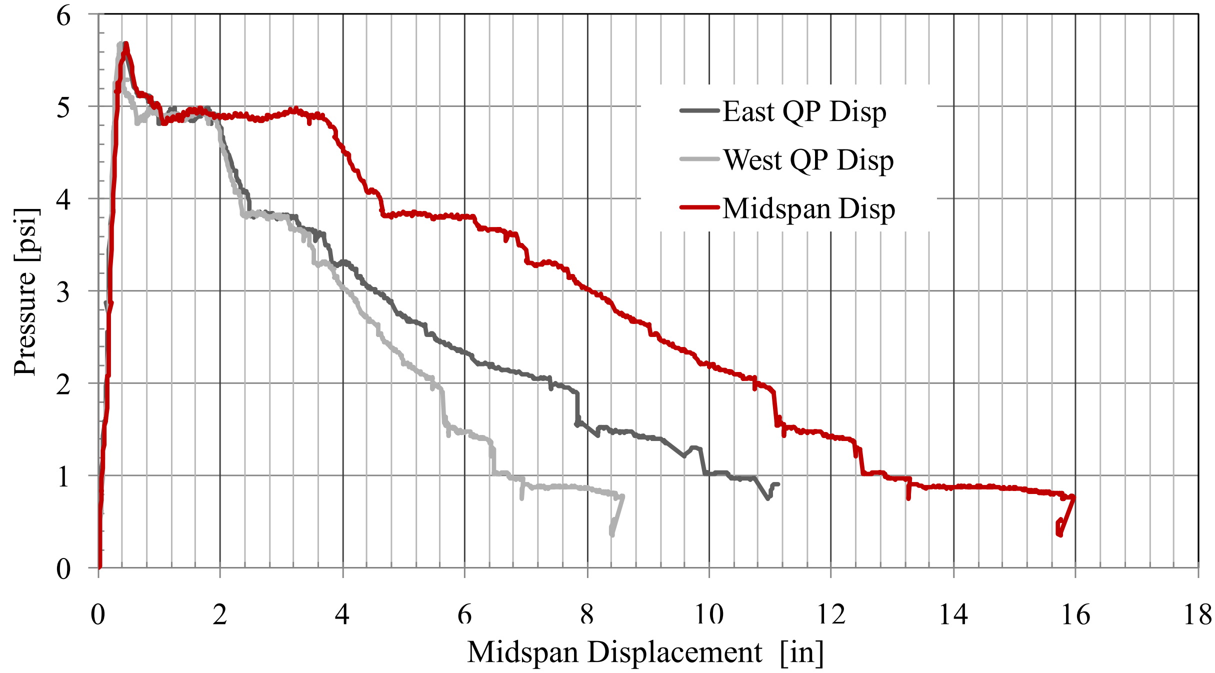


**Figure 136. Tin1-A Response**

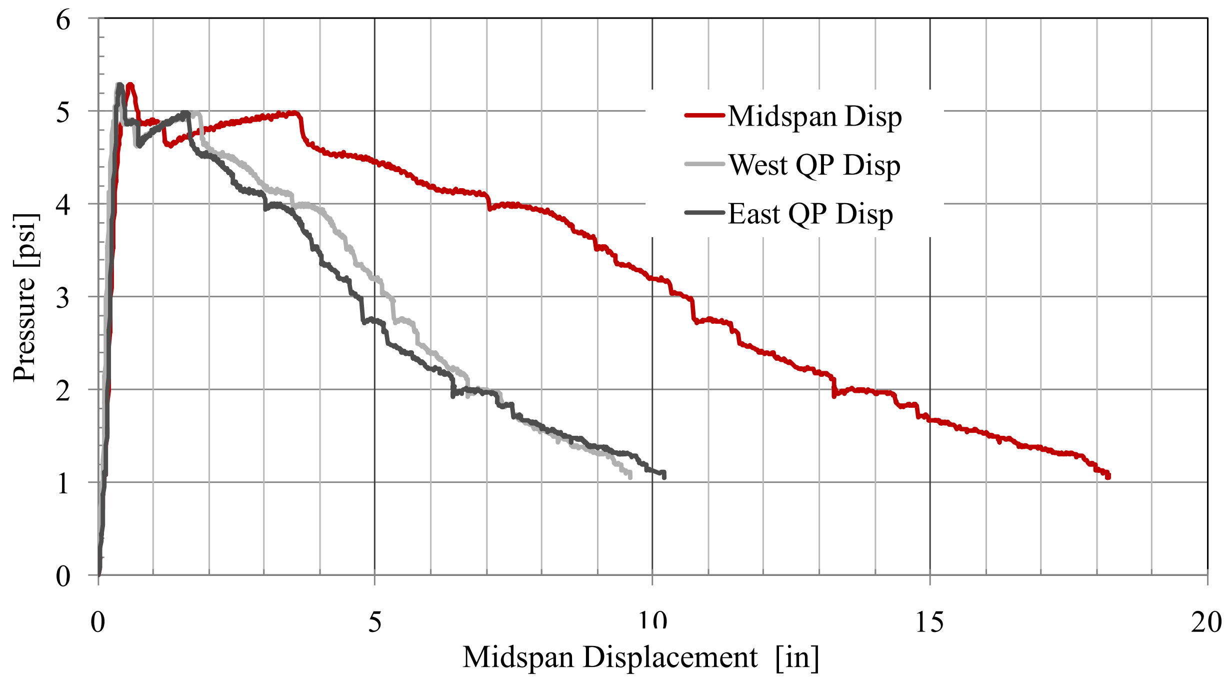


**Figure 137. Tin1-B Response**


Distribution Statement A: Approved for public release; distribution unlimited.

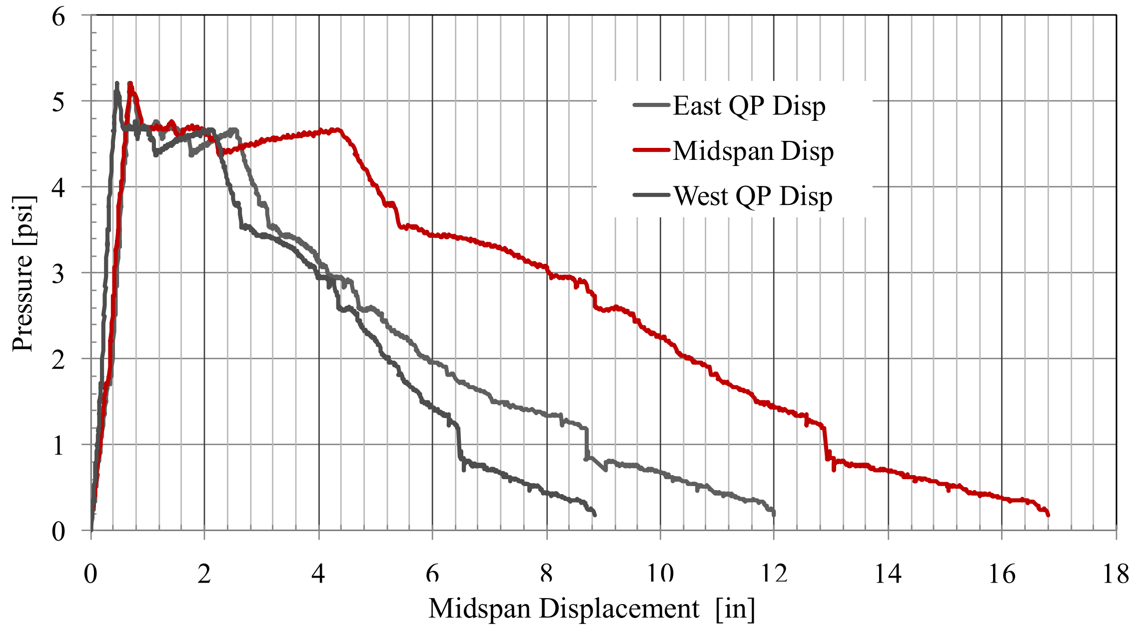


**Figure 138. Tin1-C Response**

### 6.14. Tin2 3-4-3 Specimen Performance (Unbonded)

Tin2 consists of a partially composite 3-4-3 PC CSW panel fabricated with XPS insulation and Meadow Burke steel truss girder shear ties. The panel is prestressed with conventional transverse reinforcement in both the interior and exterior wythe. The panel cross-section and reinforcement details are illustrated in Figures 139 and 140.

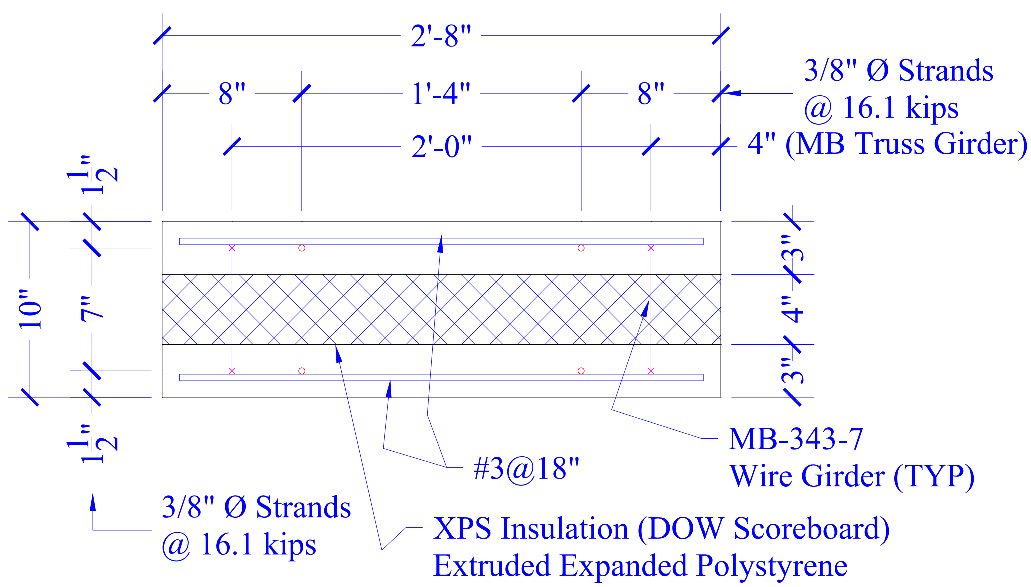


**Figure 139. Tin2 Cross-Section Detail**


Distribution Statement A: Approved for public release; distribution unlimited.

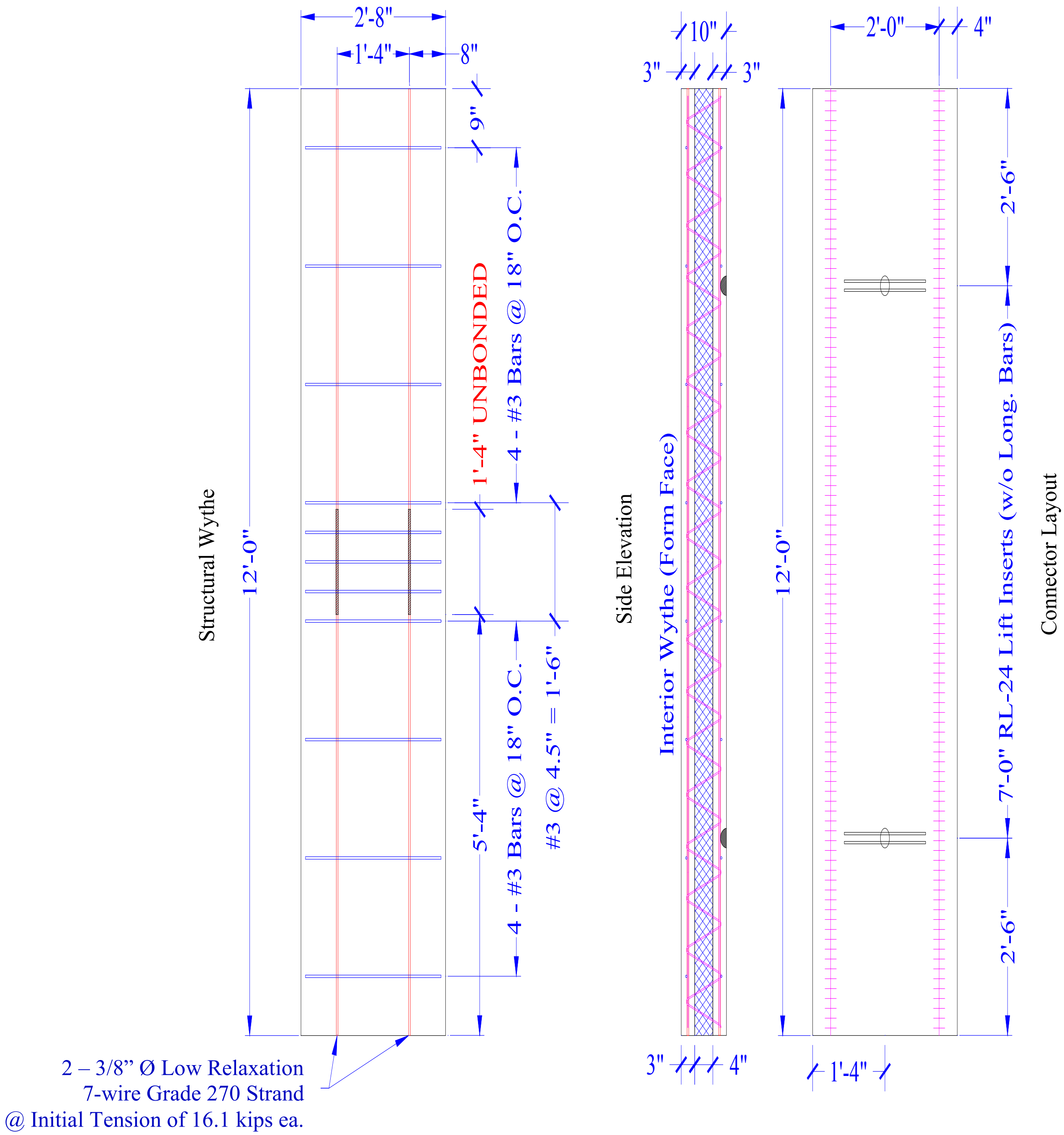


**Figure 140. Tin2 Panel Detail**

The measured response is summarized in Table 30. The midspan pressure displacement for the three specimen are in Figure 141. The individual response of each panel and the quarter point displacements are included in Figures 142-144.


Distribution Statement A: Approved for public release; distribution unlimited.

**Table 30. Tin2 Measured Response**

| Specimen | Age at Test [days] | Max Load [lbs] | Max Pressure [psi] | Corresponding Displacement [in] | East Slip [in] | West Slip [in] | Rot. [deg] | Measured Moment Capacity [k-in] |
|---|---|---|---|---|---|---|---|---|
| Tin2-A | 94 | 21847 | 5.69 | 0.84 | NA | NA | 0.802 | 327.7 |
| Tin2-B | 101 | 18635 | 4.85 | 2.89 | NA | NA | 2.758 | 279.5 |
| Tin2-C | 225 | 18987 | 4.94 | 4.35 | NA | NA | 4.157 | 284.8 |
| | Average | 19823 | 5.16 | 2.69 | NA | NA | 2.57 | 297.3 |

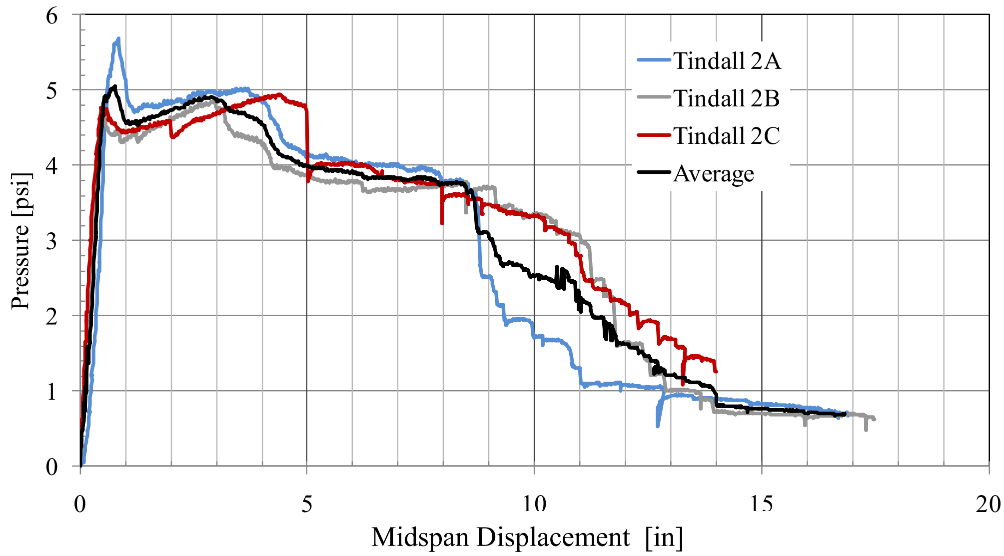


**Figure 141. Tin2 Pressure–Displacement Response**

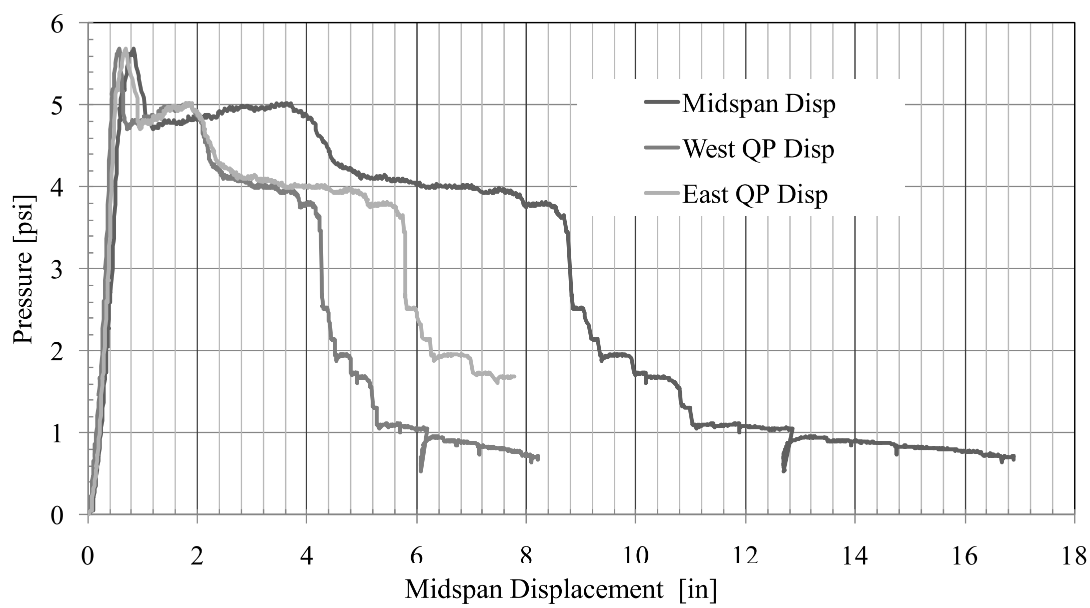


**Figure 142. Tin2-A Response**



Distribution Statement A: Approved for public release; distribution unlimited.

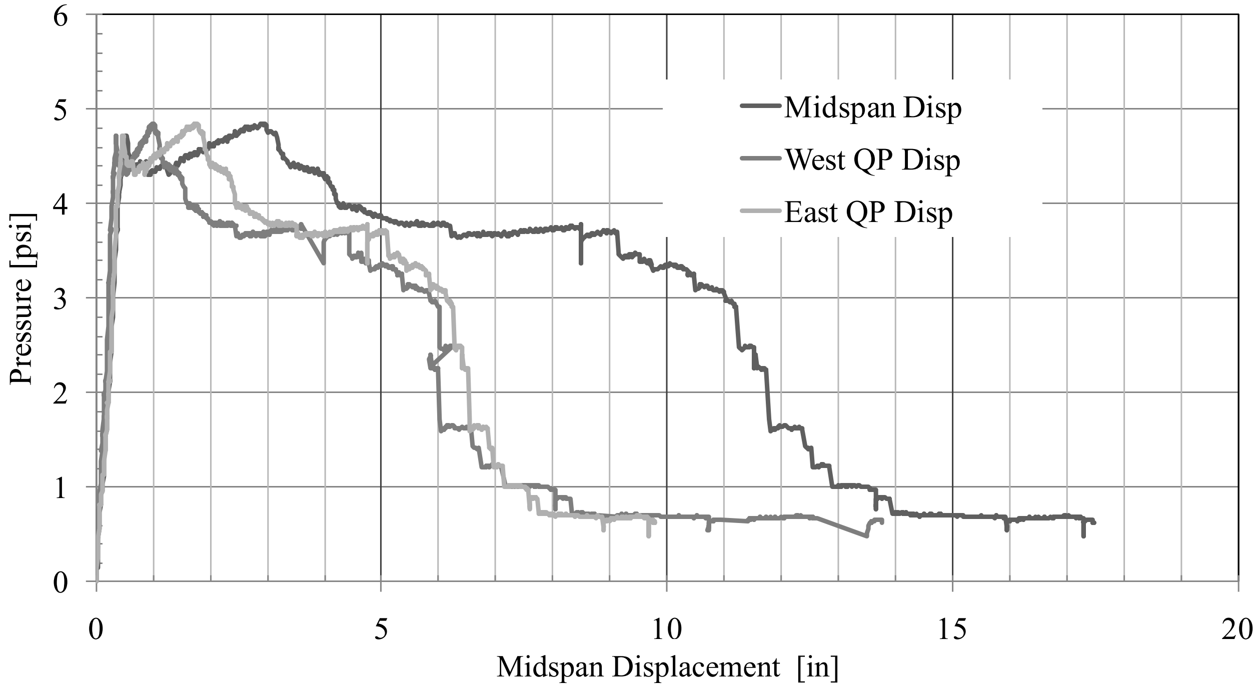


**Figure 143. Tin2-B Response**

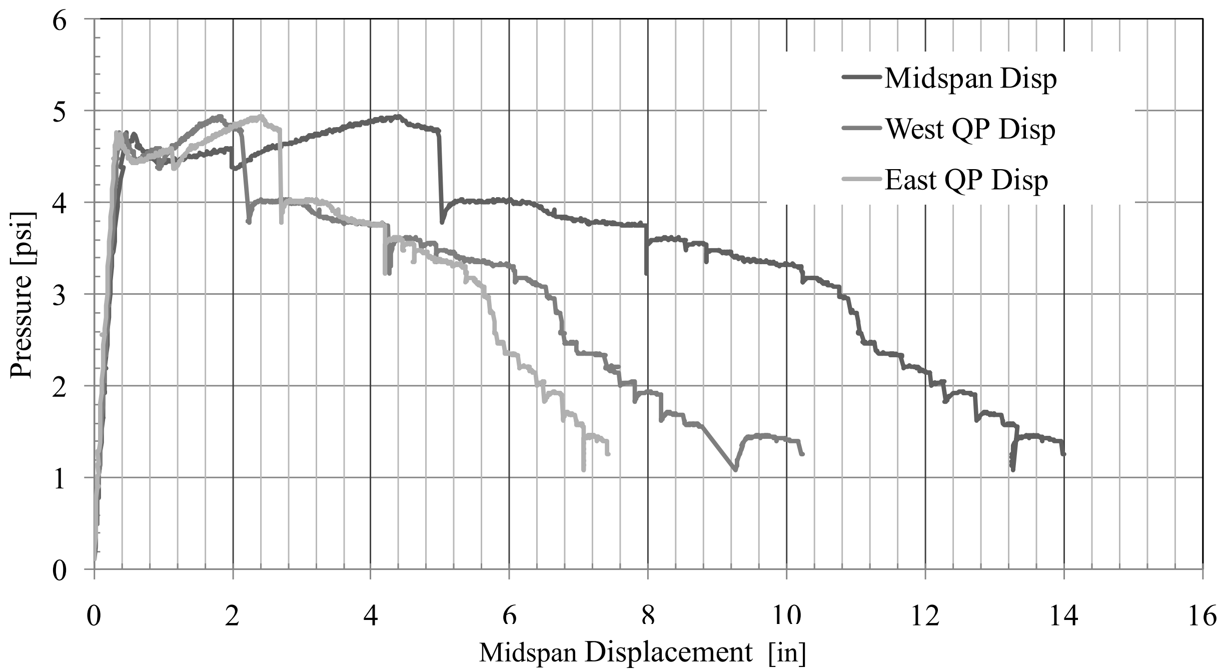


**Figure 144. Tin2-C Response**


Distribution Statement A: Approved for public release; distribution unlimited.

## 7. SINGLE-SPAN PANELS WITH END CONNECTION RESULTS

### 7.1. PCS10 3-3-3 Specimen Performance

PCS10 consists of a partially composite 3-3-3 PC CSW panel fabricated with XPS insulation and carbon fiber C-Grid® shear ties. The panel is prestressed with WWR transverse reinforcement in both the interior and exterior wythe. The panel cross-section and reinforcement details are illustrated in Figures 145 and 146.

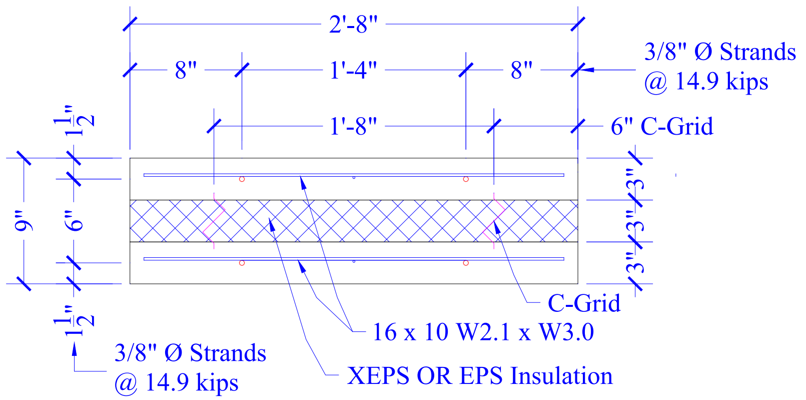


**Figure 145. PCS10 Cross-Section Detail**

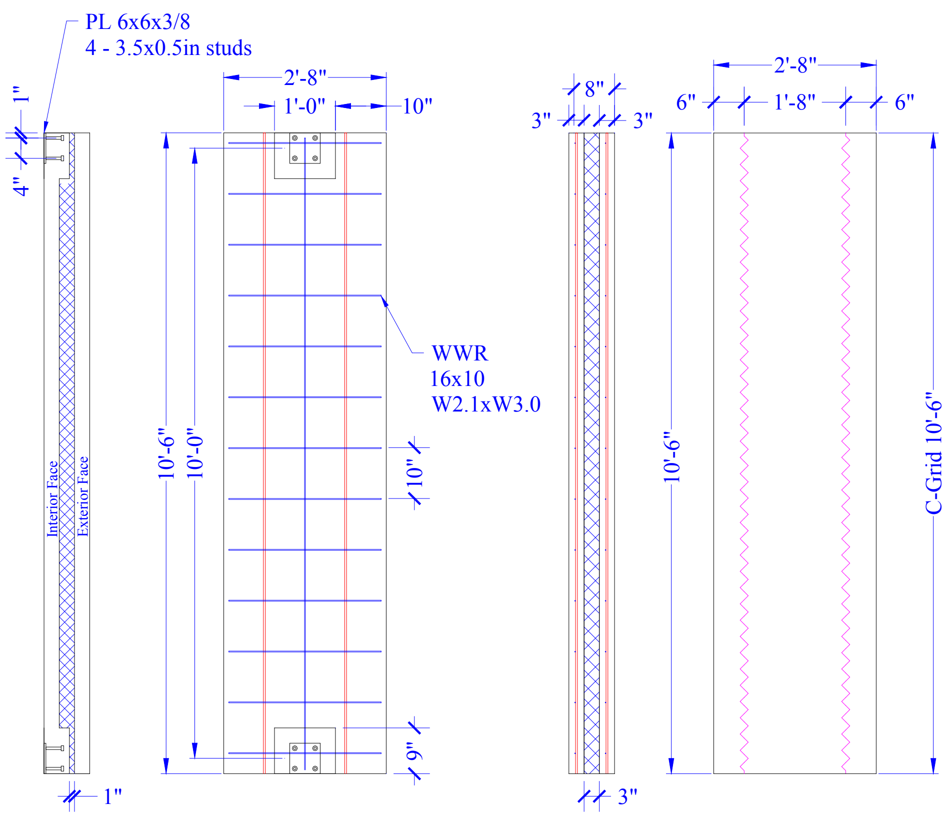


**Figure 146. PCS10 Panel Detail**


Distribution Statement A: Approved for public release; distribution unlimited.

The measured response is summarized in Table 31. The midspan pressure displacement and moment-support rotation for the two specimen are in Figures 147 and 148. The individual response of each panel and the displacement and rotation responses are included in Figures 149 and 150. Figures 151 and 152 show a picture representation of the samples post-test.

The rebound response exhibited less ductility and strength than that of the inbound response. The reduction was due to the failure of the panel at the support and failure of the stud group weld to the plate as illustrated in the images in Figure 152.

**Table 31. PCS10 Measured Response**

| Specimen | Age at Test [days] | Max Load [lbs] | Max Pressure [psi] | Corresponding Displacement [in] | East Slip [in] | West Slip [in] | Rot. [deg] | Measured Moment Capacity [k-in] |
|---|---|---|---|---|---|---|---|---|
| PCS10-A | 72 | 19785 | 5.152 | 2.248 | - | - | 2.145 | 296.78 |
| PCS10-B | 85 | 17007 | 4.429 | 1.283 | - | - | 1.225 | 255.11 |
| | Average | 18396 | 4.791 | 1.765 | - | - | 1.685 | 275.94 |

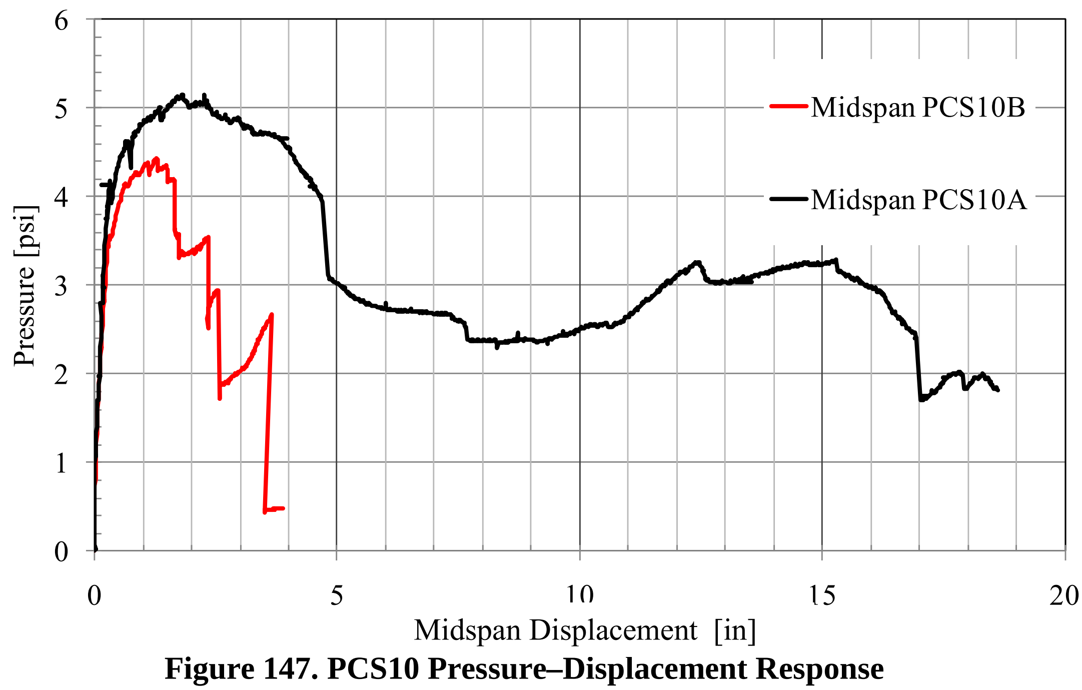


**Figure 147. PCS10 Pressure–Displacement Response**


Distribution Statement A: Approved for public release; distribution unlimited.

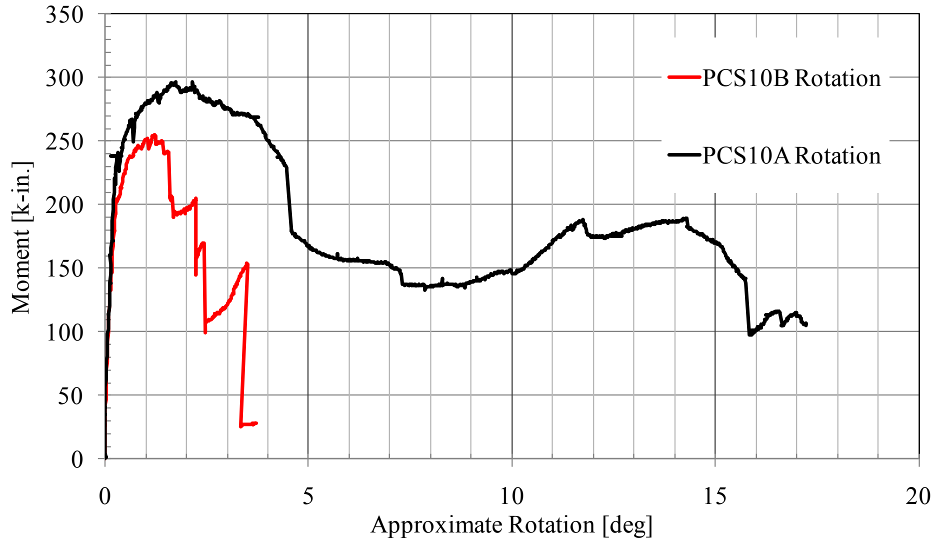


**Figure 148. PCS10 Moment–Rotation Response**

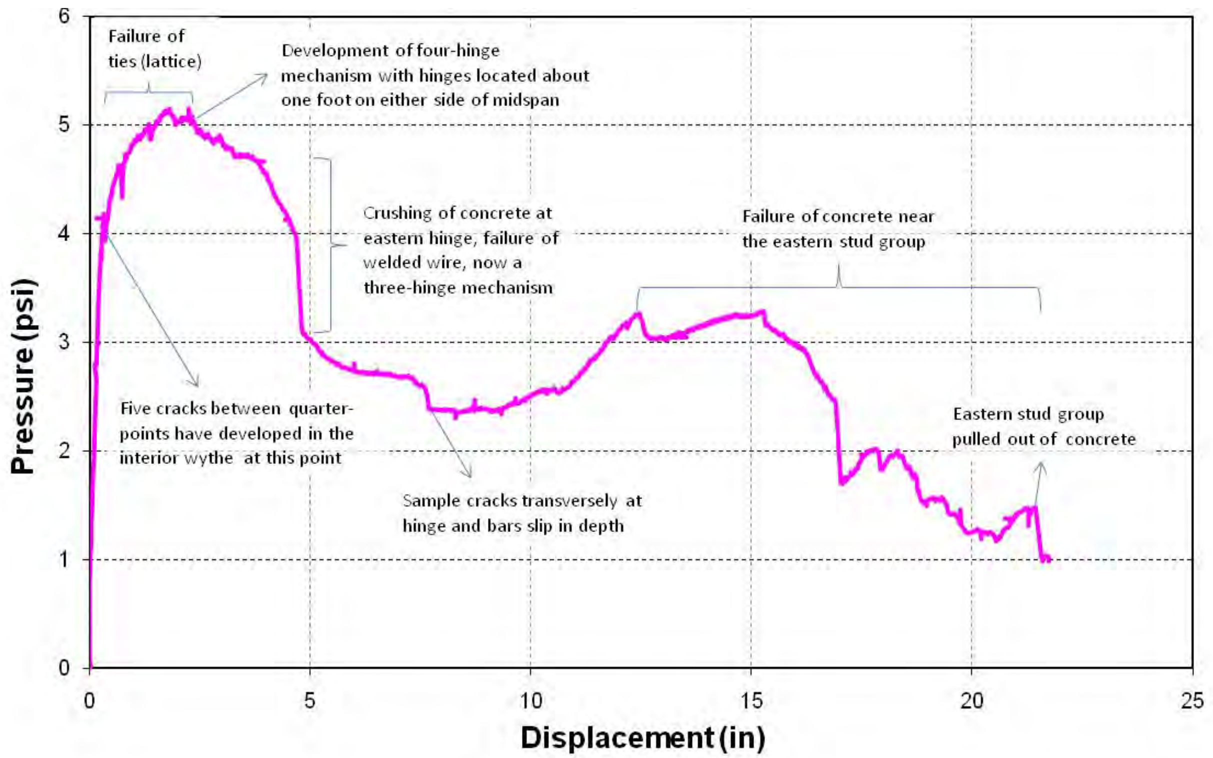


**Figure 149. PCS10-A Inbound Response**



Distribution Statement A: Approved for public release; distribution unlimited.

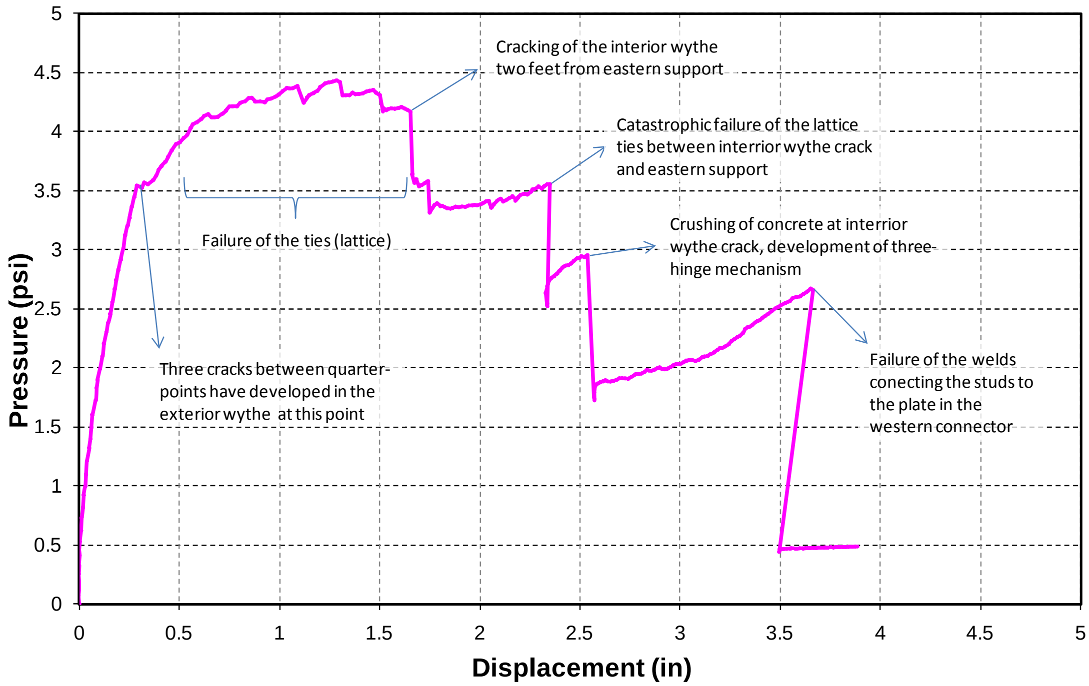


**Figure 150. PCS10-B Rebound Response**

**Figure 151. PCS10-A Inbound Response**


Distribution Statement A: Approved for public release; distribution unlimited.

**Figure 152. PCS10-B Rebound Response**

## 7.2. PCS11 3-3-3 Specimen Performance

PCS11 consists of a partially composite 3-3-3 PC CSW panel fabricated with XPS insulation and glass fiber THERMOMASS® composite shear pins. The panel is prestressed with WWR transverse reinforcement in both the interior and exterior wythe. The panel cross-section and reinforcement details are illustrated in Figures 153 and 154.


Distribution Statement A: Approved for public release; distribution unlimited.

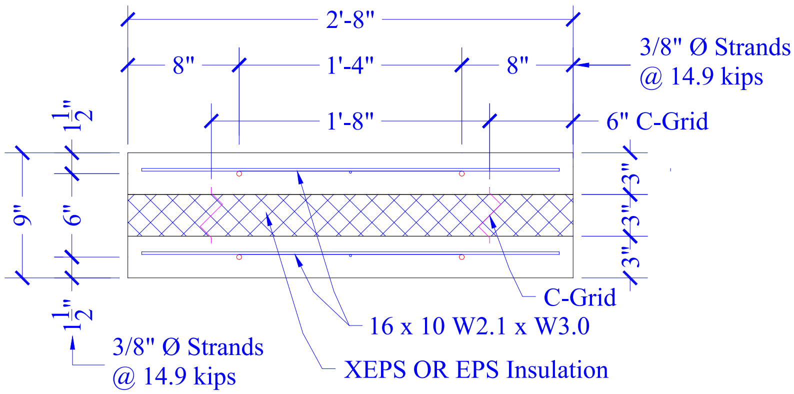


**Figure 153. PCS11 Cross-Section Detail**

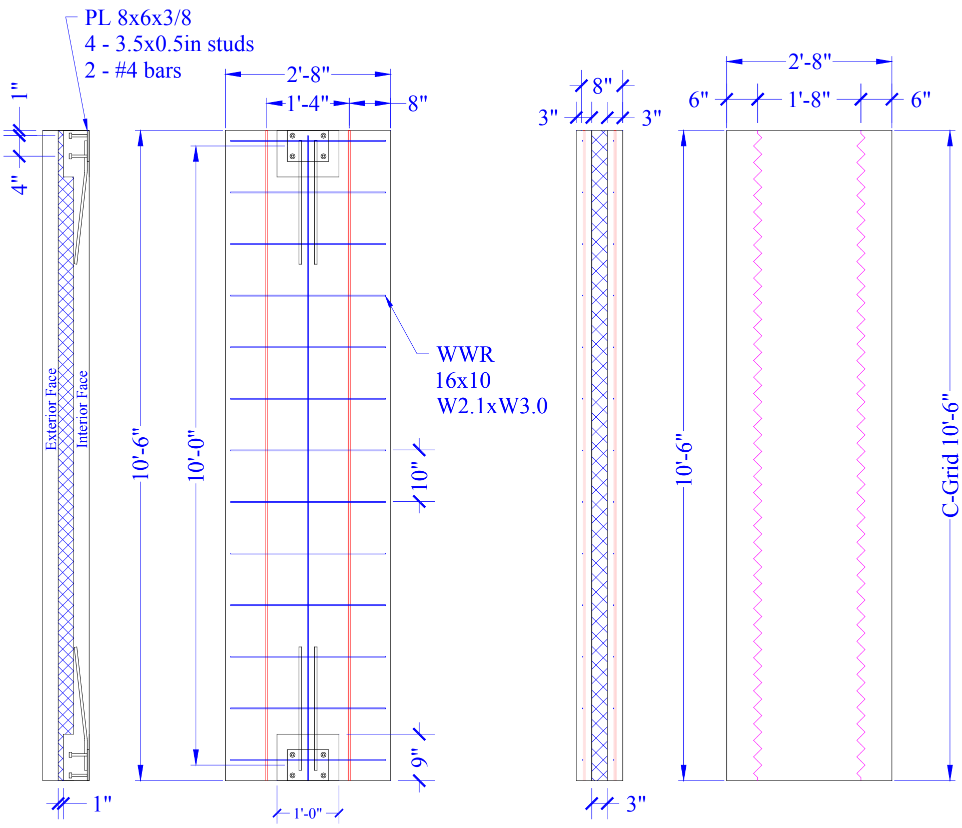


**Figure 154. PCS 11 Panel Detail**

The measured response is summarized in Table 32. The midspan pressure displacement and moment–support rotation for the two specimen are in Figures 155 and 156. The individual response of each panel and the displacement and rotation responses are included in Figures 157 and 158. Figures 159 and 160 show a picture representation of the samples post-test.

The rebound response exhibited less ductility and strength than that of the inbound response. The reduction was due to the failure of the panel at the support and failure of the stud group weld to the plate as illustrated in the images in Figure 160.


Distribution Statement A: Approved for public release; distribution unlimited.

**Table 32. PCS11 Measured Response**

| Specimen | Age at Test [days] | Max Load [lbs] | Max Pressure [psi] | Corresponding Displacement [in] | East Slip [in] | West Slip [in] | Rot. [deg] | Measured Moment Capacity [k-in] |
|---|---|---|---|---|---|---|---|---|
| PCS11-A | 72 | 18956 | 4.936 | 2.386 | - | - | 2.277 | 284.33 |
| PCS11-B | 86 | 22039 | 5.739 | 3.521 | - | - | 3.359 | 330.59 |
| | Average | 20497 | 5.34 | 2.95 | - | - | 2.82 | 307.5 |

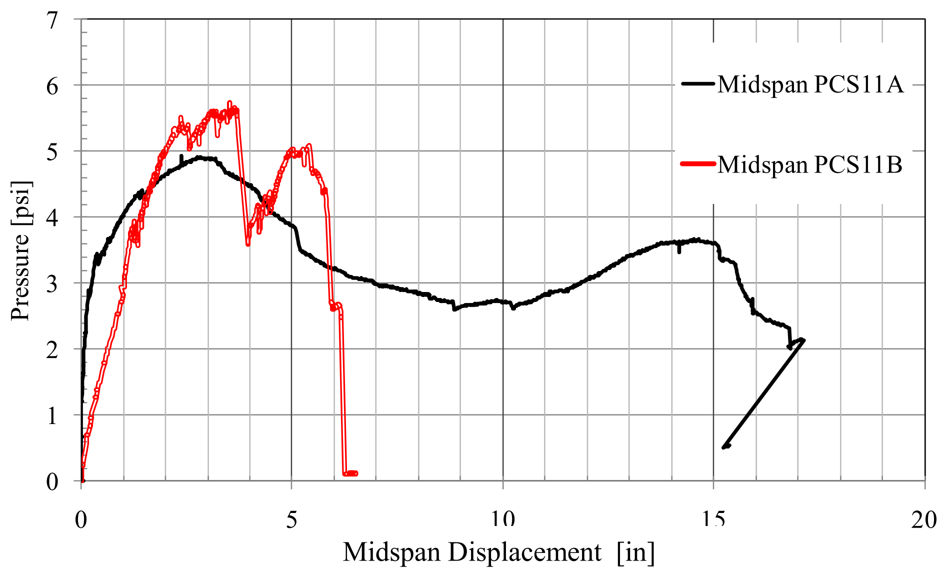


**Figure 155. PCS11 Pressure–Displacement Response**

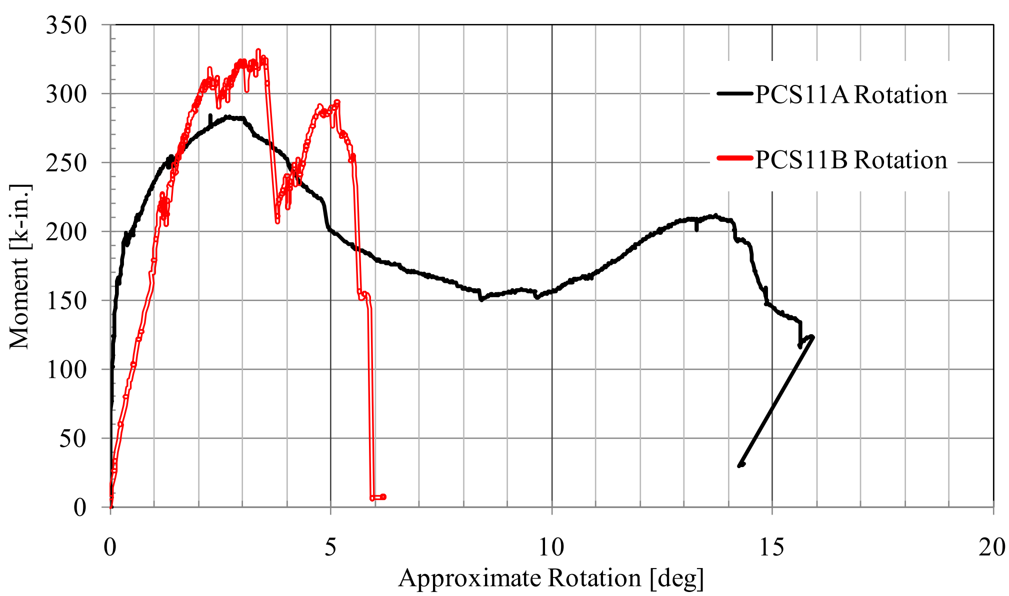


**Figure 156. PCS11 Moment–Rotation Response**


Distribution Statement A: Approved for public release; distribution unlimited.

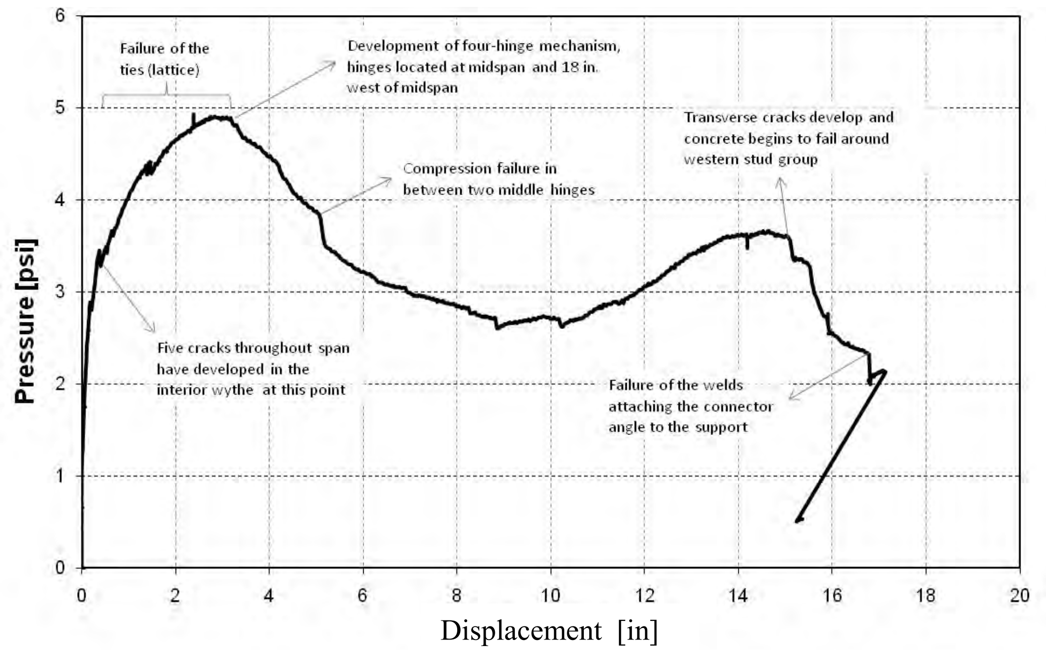


**Figure 157. PCS11-A Response**

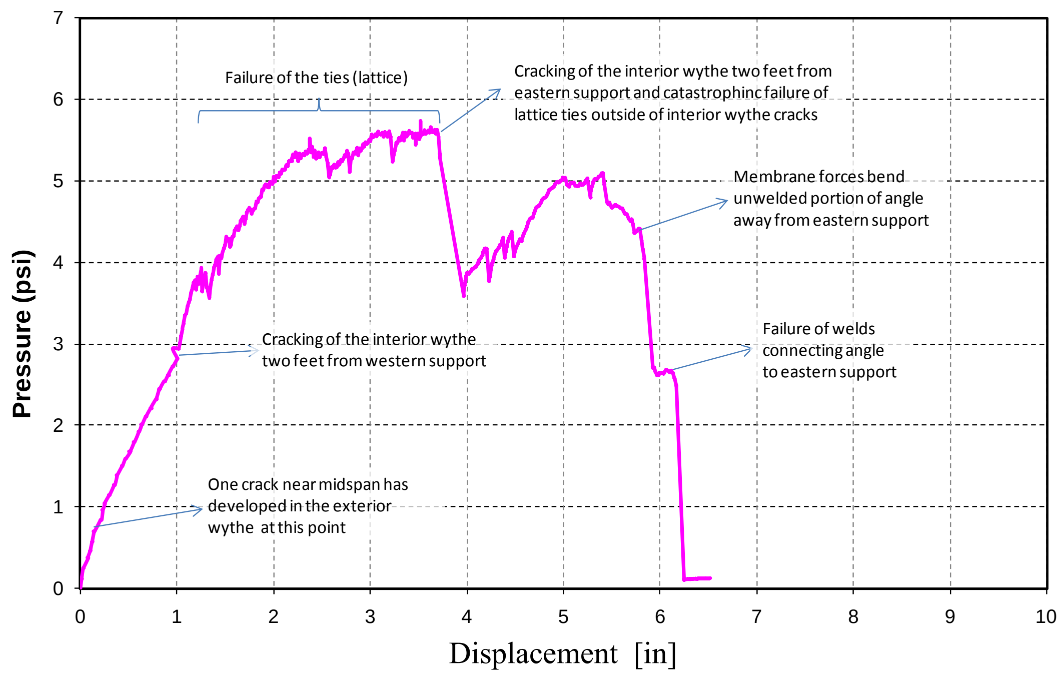


**Figure 158. PCS11-B Response**


Distribution Statement A: Approved for public release; distribution unlimited.

**Figure 159. PCS11 Panel Inbound Response (A)**

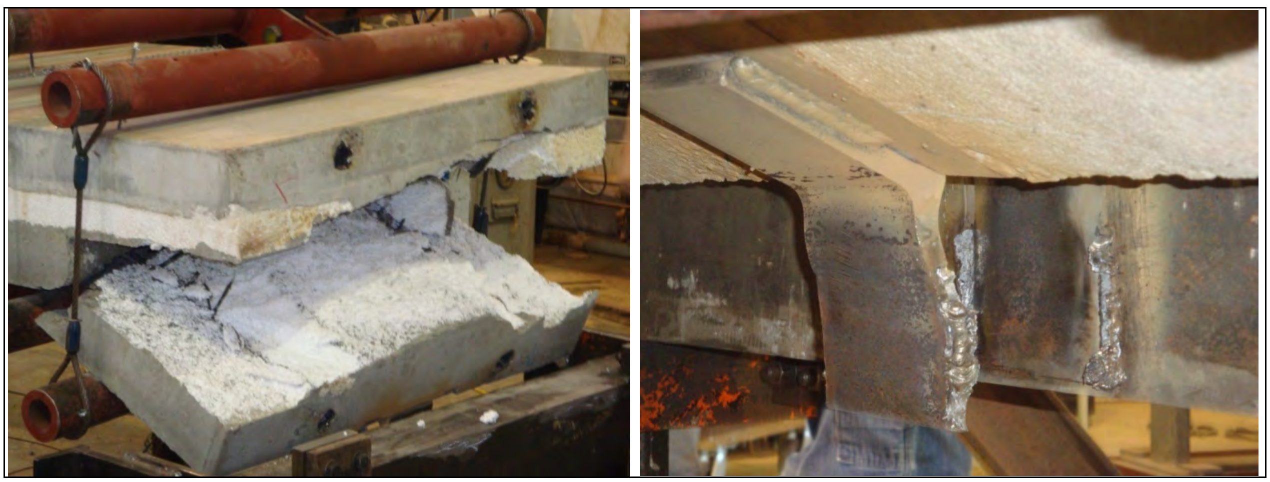

**Figure 160. PCS11 Panel Rebound Response (B)**



Distribution Statement A: Approved for public release; distribution unlimited.

## 8. MULTI SPAN PANEL RESULTS

### 8.1. PCD1 3-3-3 Specimen Performance

PCD1 consists of two-span partially composite 3-3-3 PC CSW panel fabricated with XPS insulation and glass fiber THERMOMASS® composite shear pins. The panel is prestressed with WWR transverse reinforcement in both the interior and exterior wythe. The panel cross-section and reinforcement details are illustrated in Figures 161 and 162.

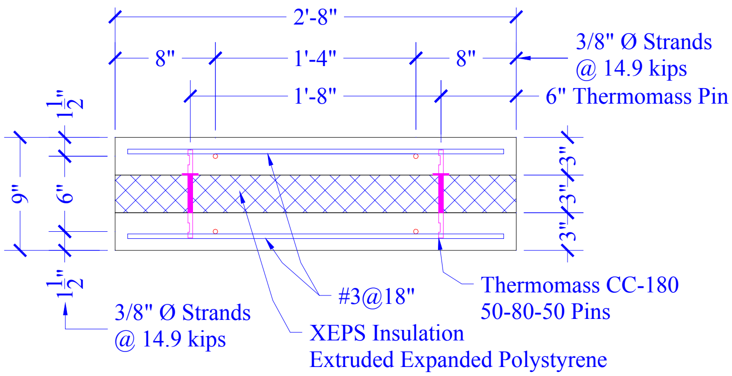


**Figure 161. PCD1 Cross-Section Detail**

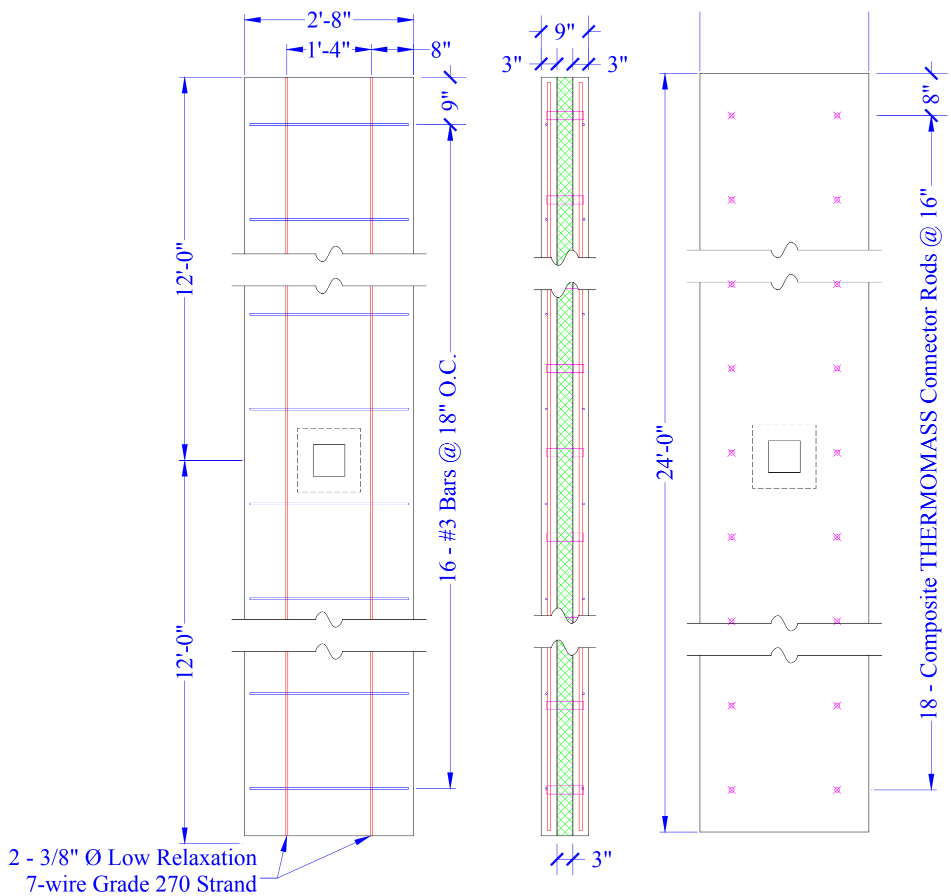


**Figure 162. PCD1 Panel Detail**


Distribution Statement A: Approved for public release; distribution unlimited.

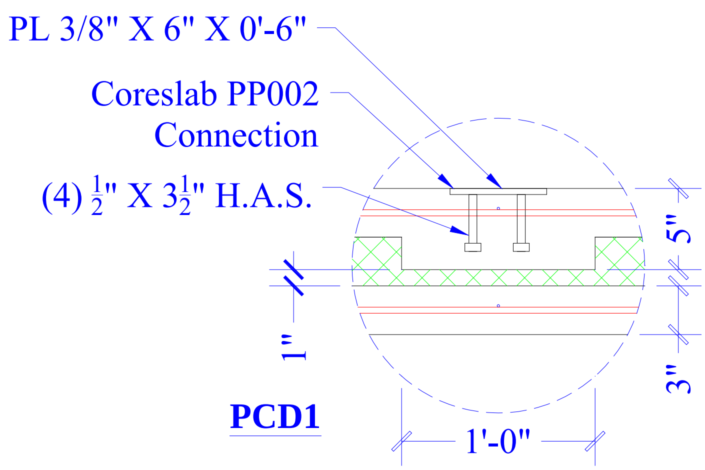


**Figure 163. Coreslab Two-span Panel PCD1 Midspan Connection**

The material properties for the specimen and the measured response are summarized in Table 16 and Table 34. The midspan pressure displacement for the three specimen follows in Figure 164. The individual response of each panel and the end slips, damage photos, and quarter point displacements are included in Figures 165-171.

**Table 33. PCD1 Materials Properties**

| Property | Value |
|---|---|
| Design Unit Weight | 150 pcf |
| Design Compression Strength at Release, $f_{ci}$ | 3500 psi |
| Design Compressive Strength at 28-days. $f'_c$ | 5000 psi |
| Approximate Compressive Strength PCD1A | 9228 psi |
| Approximate Compressive Strength PCD1B | 9201 psi |
| Approximate Compressive Strength PCD1-B | 9192 psi |

**Table 34. PCD1 Measured Response**

| Specimen | Age at Test [days] | Max Load [lbs] | Max Pressure [psi] | East Corresponding Displacement [in] | West Corresponding Displacement [in] | East Slip [in] | West Slip [in] | Measured (+) Moment Capacity ($9/64wL^2$) | Measured (-) Moment Capacity ($1/4*wL^2$) |
|---|---|---|---|---|---|---|---|---|---|
| PCD1-A | 60 | 34865.6 | 4.006 | 5.574 | 4.736 | 0.487 | 0.288 | 333.4 | 593 |
| PCD1-B | 63 | 34731.4 | 3.990 | 2.727 | 2.885 | 0.175 | 0.158 | 332.1 | 590 |
| PCD1-C | 64 | 36338.5 | 4.175 | 7.284 | 4.741 | 0.514 | 0.477 | 347.5 | 618 |
| | Average | 35311.8 | 4.057 | 5.195 | 4.121 | 0.392 | 0.308 | 337.7 | 600.3 |


Distribution Statement A: Approved for public release; distribution unlimited.

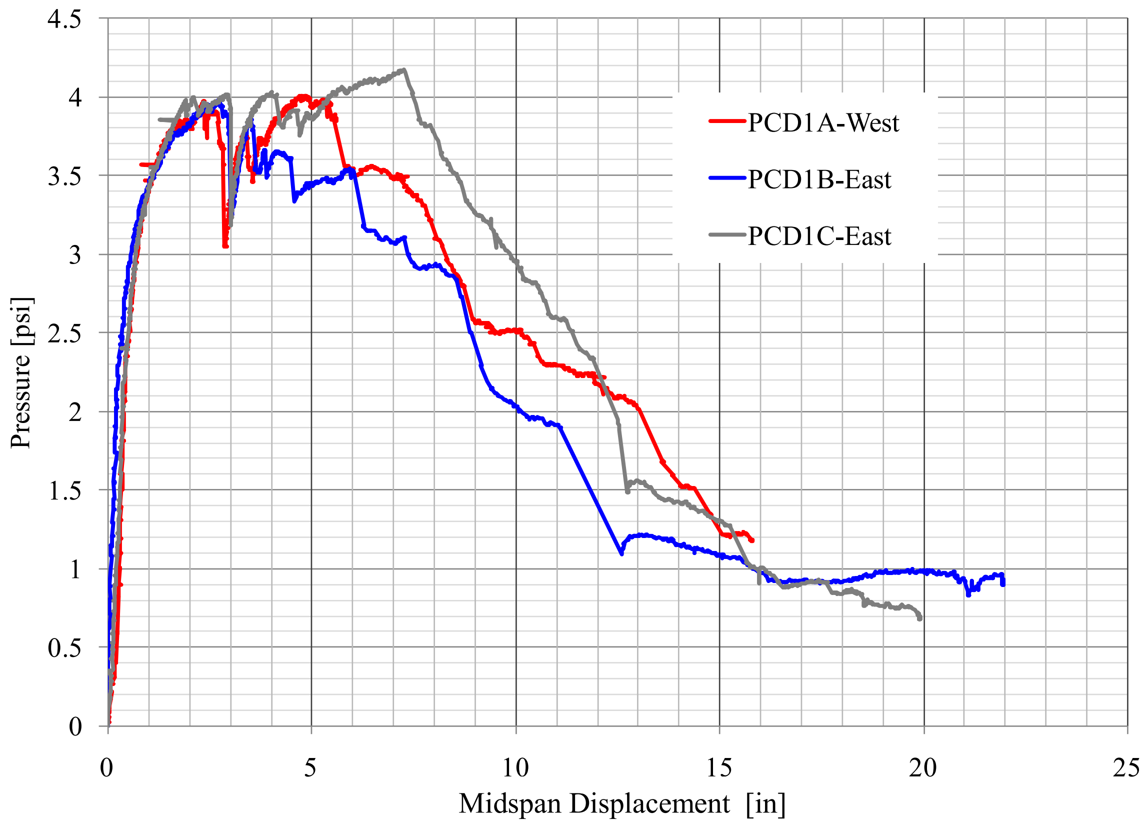


**Figure 164. PCD1 Pressure–Displacement Response**

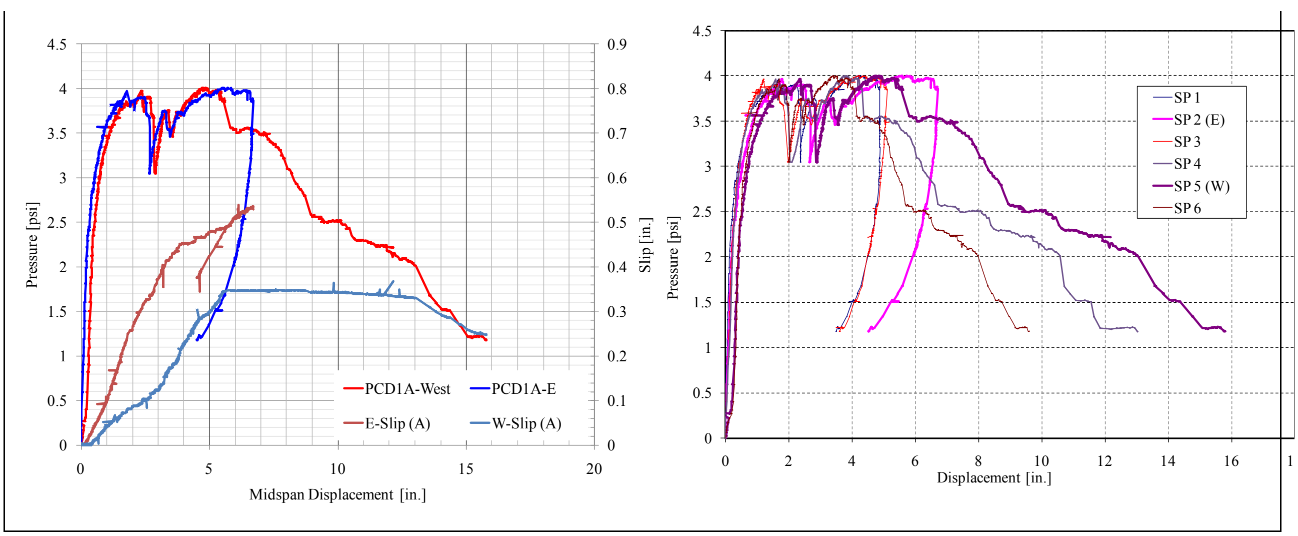


**Figure 165. PCD1-A Response**


Distribution Statement A: Approved for public release; distribution unlimited.

**Figure 166. PCSD1-A Punching Failure of Connection**

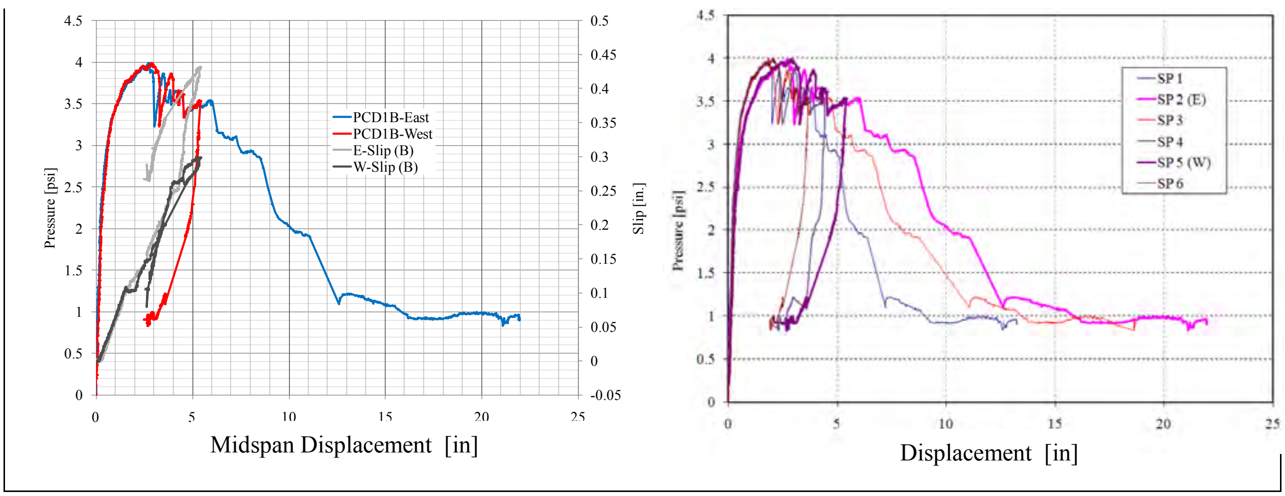


**Figure 167. PCD1-B Response**

**Figure 168. PCD1-B Punching Failure of Connection**


Distribution Statement A: Approved for public release; distribution unlimited.

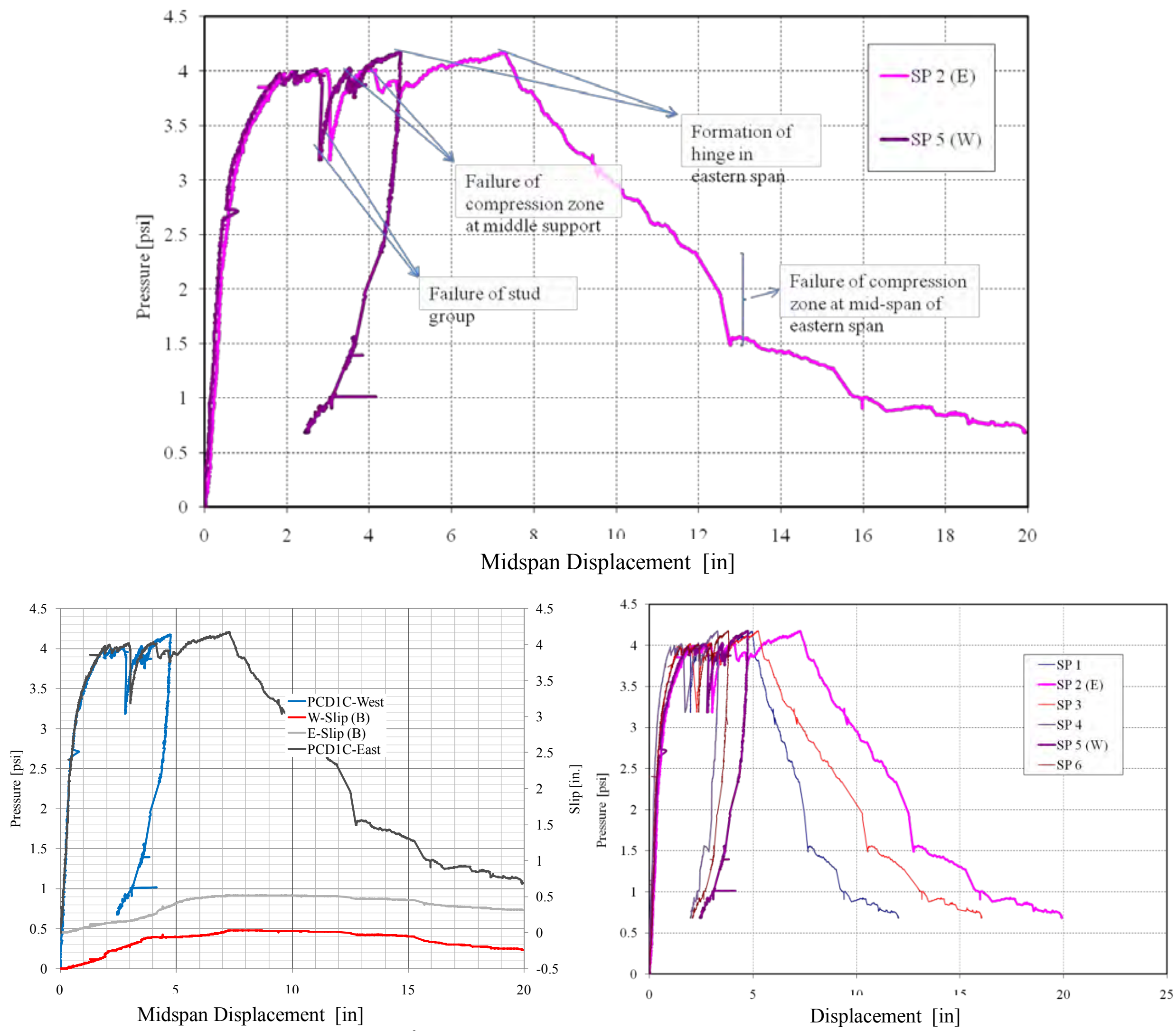


**Figure 169. PCD1-C Response**

**Figure 170. PCD1-C Punching Failure of Connection**


Distribution Statement A: Approved for public release; distribution unlimited.


**Figure 171. PCD1-C Failure of Panel**

### 8.2. PCD2 3-3-3 Specimen Performance

PCD2 consists of a partially composite 3-2-3 PC CSW panel fabricated with EPS insulation and carbon fiber C-Grid® shear ties. The panel is prestressed with WWR transverse reinforcement in both the interior and exterior wythe. The panel cross-section and reinforcement details are illustrated in Figures 172 and 173. The midspan support connection is shown in Figure 174.

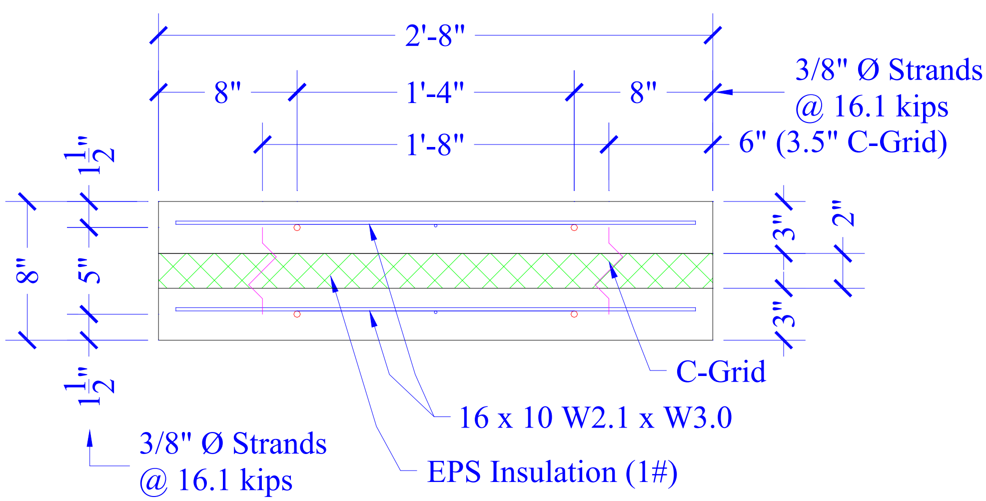


**Figure 172. PCD2 Cross-Section Detail**


Distribution Statement A: Approved for public release; distribution unlimited.

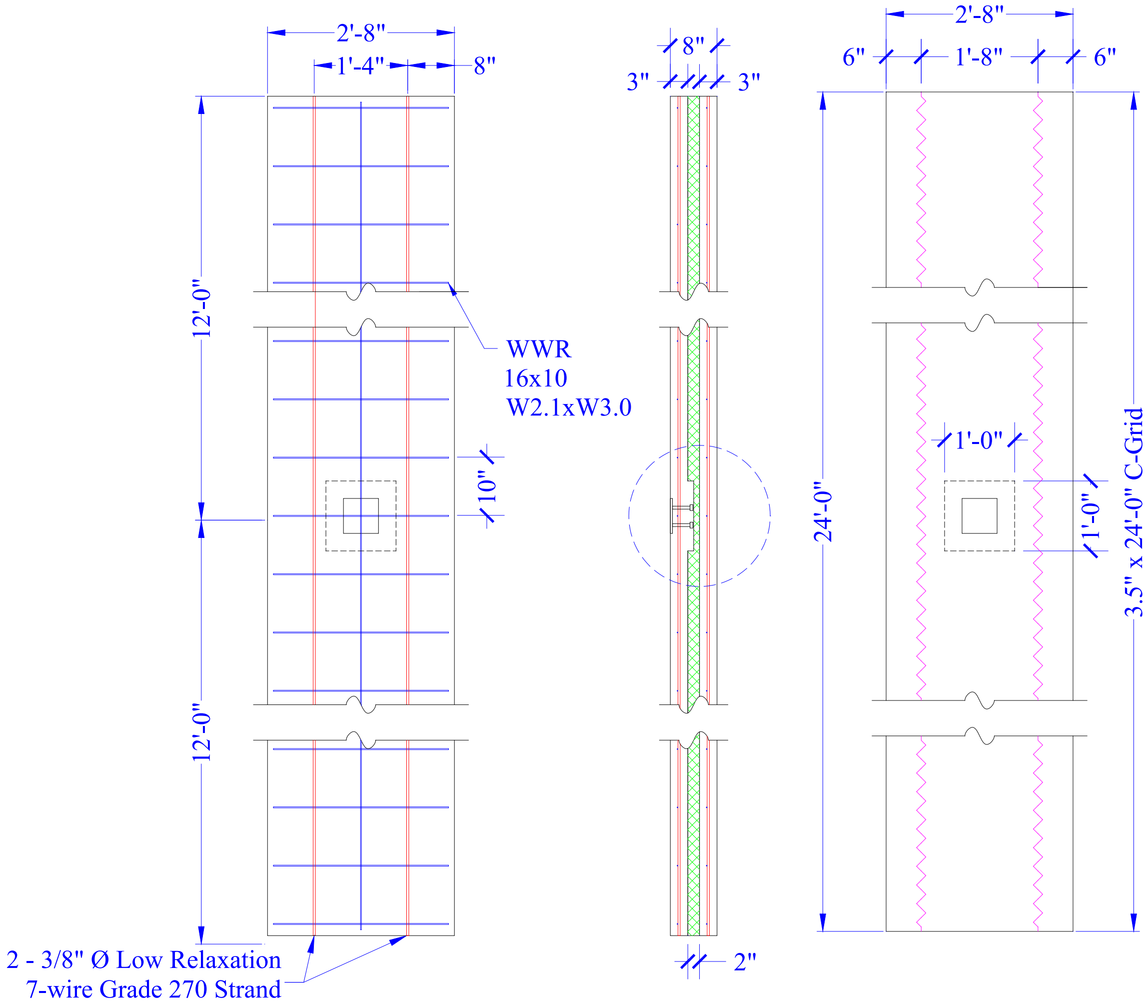


**Figure 173. PCD2 Panel Detail**

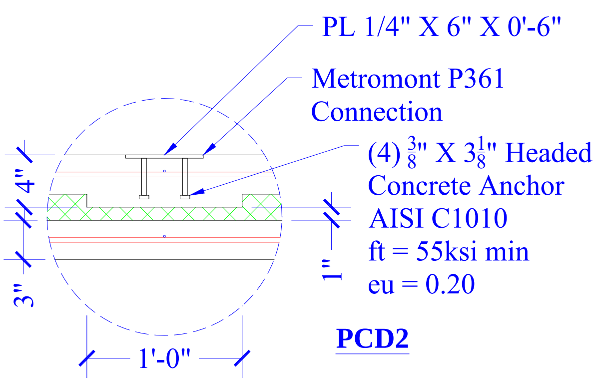


**Figure 174. PCD2 Midspan Connection Detail**

The measured response is summarized in Table 35. The midspan pressure displacement for the three specimen follows in Figure 175. The individual response of each panel and the end slips, damage photos, and quarter point displacements are included in Figures 176 through 179.


Distribution Statement A: Approved for public release; distribution unlimited.

**Table 35. PCD2 Measured Response**

| Specimen | Age at Test [days] | Max Load [lbs] | Max Pressure [psi] | East Corresponding Displacement [in] | West Corresponding Displacement [in] | East Slip [in] | West Slip [in] | Measured (+) Moment Capacity ($9/64wL^2$) | Measured (-) Moment Capacity ($1/4*wL^2$) |
|---|---|---|---|---|---|---|---|---|---|
| PCD2-A | 28 | 36762.0 | 4.224 | 3.295 | 3.620 | 0.155 | 0.289 | 351.5 | 625 |
| PCD2-B | 29 | 42539.2 | 4.887 | 0.499 | 2.580 | 0.002 | 0.157 | 406.8 | 723 |
| PCD2-C | 30 | 40551.5 | 4.659 | 1.709 | 0.738 | 0.033 | 0.002 | 387.8 | 689 |
| | Average | 39950.9 | 4.590 | 1.834 | 2.312 | 0.063 | 0.149 | 382.0 | 679 |

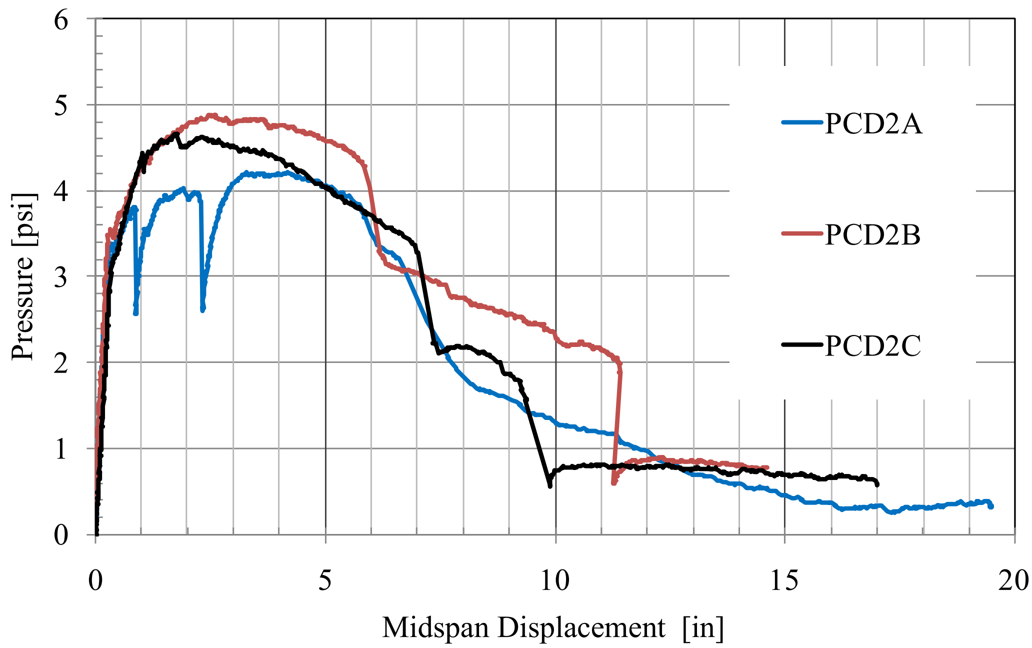


**Figure 175. PCD2 Pressure–Displacement Response**


Distribution Statement A: Approved for public release; distribution unlimited.

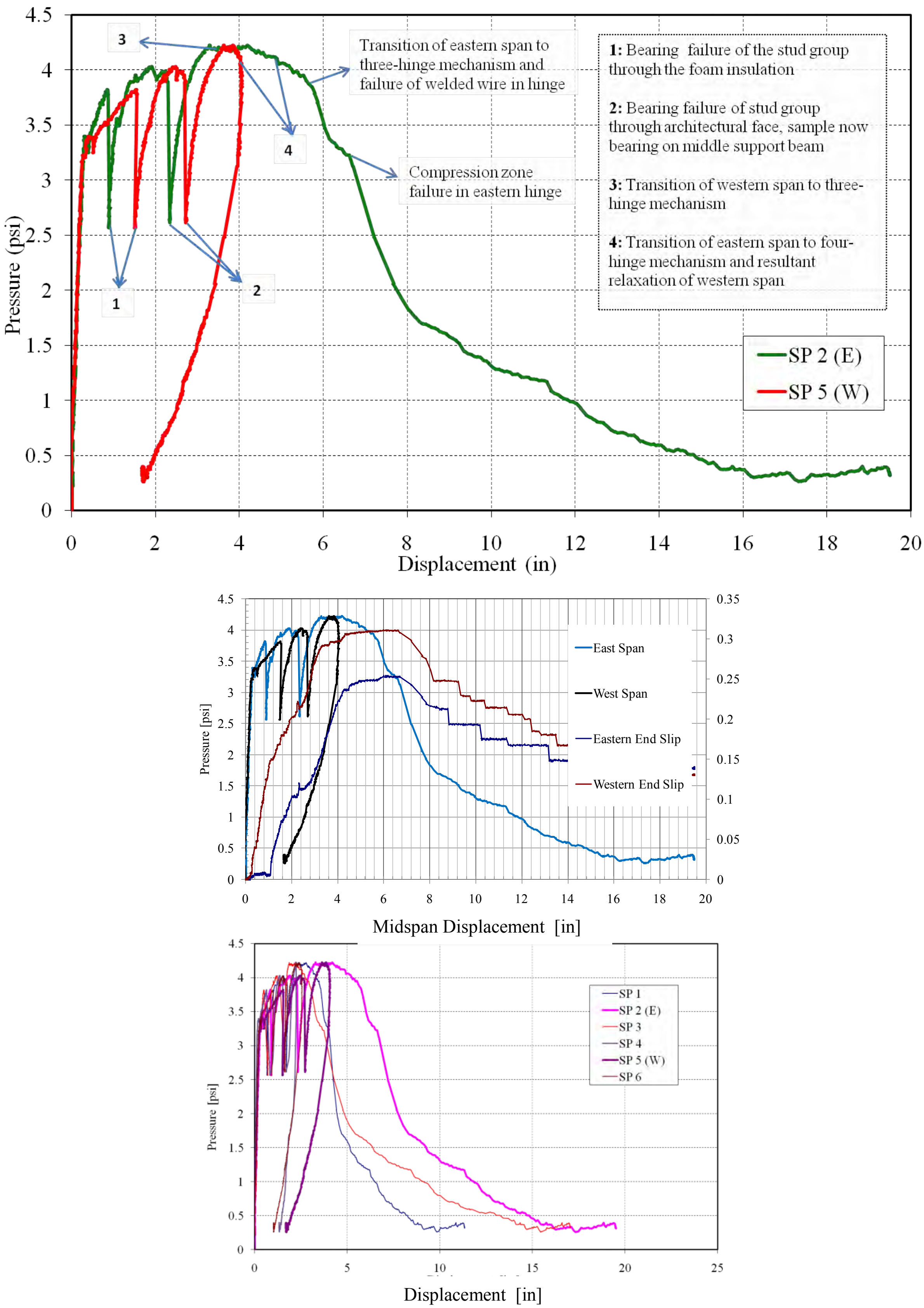


**Figure 176. PCD2-A Response**


Distribution Statement A: Approved for public release; distribution unlimited.

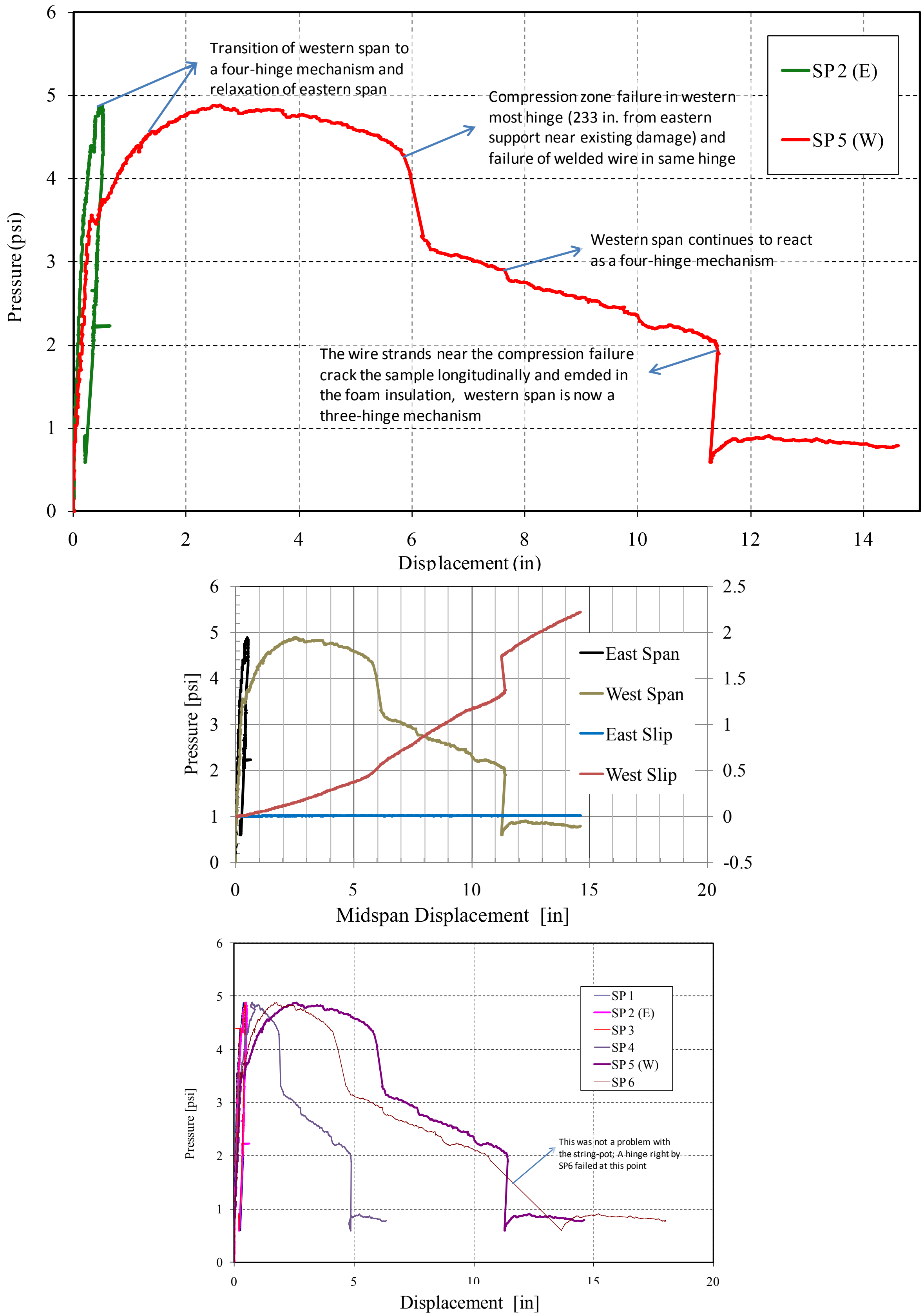


**Figure 177. PCD2-B Response**



Distribution Statement A: Approved for public release; distribution unlimited.

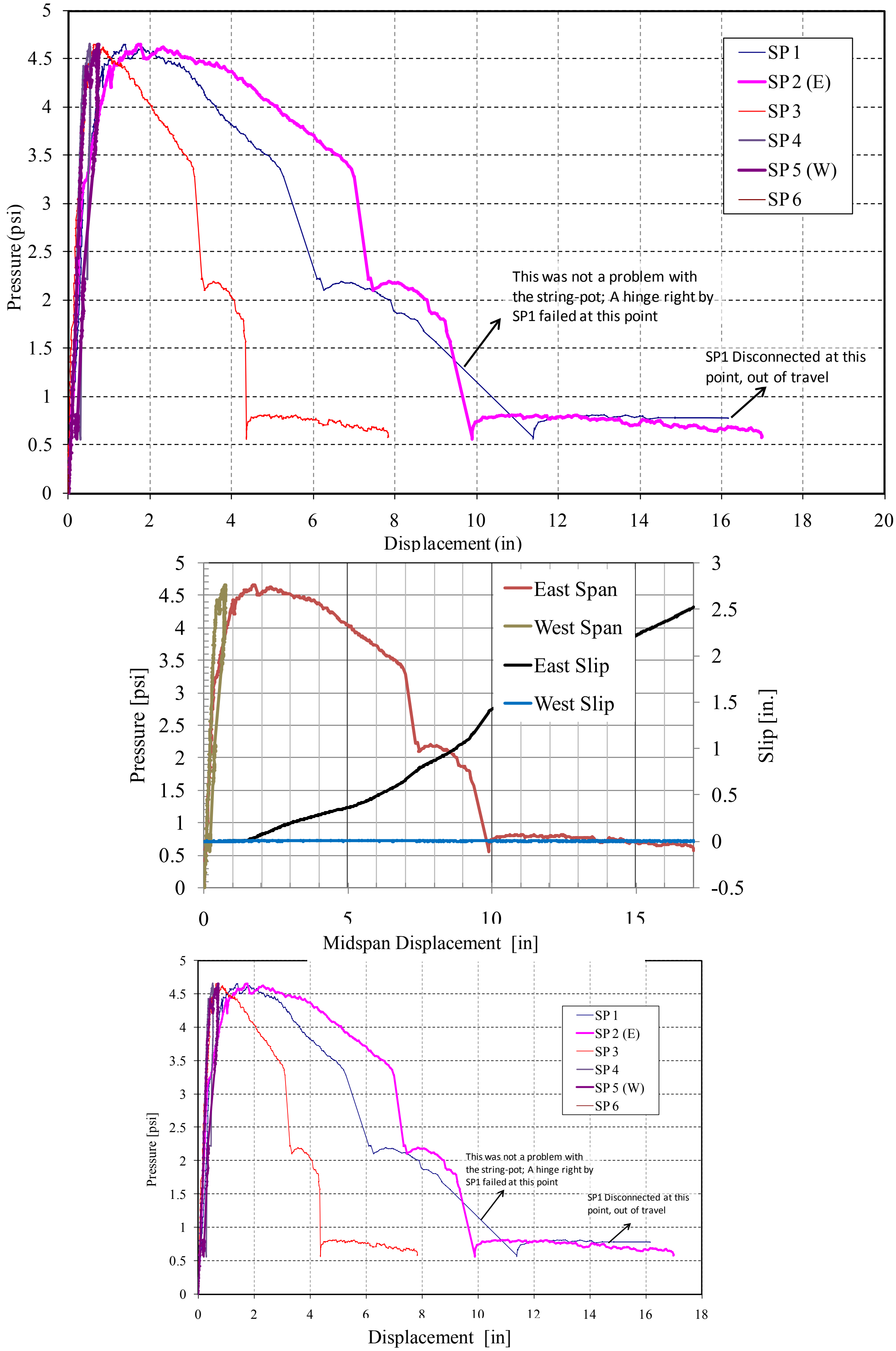


**Figure 178. PCD2-C Response**



Distribution Statement A: Approved for public release; distribution unlimited.

**Figure 179. PCD2 Panel Response (A, B, C)**

## 8.3. TS3-A and B 6-2-3 Specimen Performance

TS3-A and B consist of a non-composite 6-2-3 PC CSW panel fabricated with XPS insulation and glass fiber THERMOMASS® non-composite shear pins. The panel is conventionally reinforced with rebar transverse reinforcement in the interior wythe and WWR in the exterior wythe. The panel cross-section and reinforcement details are illustrated in Figures 180 and 181. The midspan connection detail is illustrated in Figure 182.

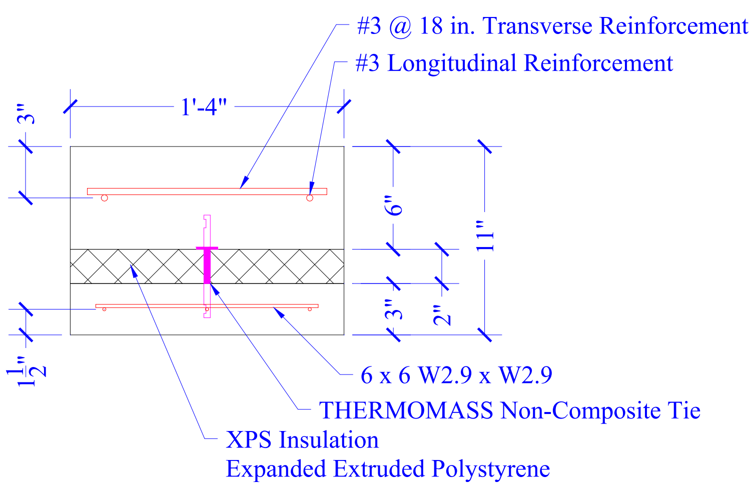


**Figure 180. TS3-A, B Cross-Section Detail**


Distribution Statement A: Approved for public release; distribution unlimited.

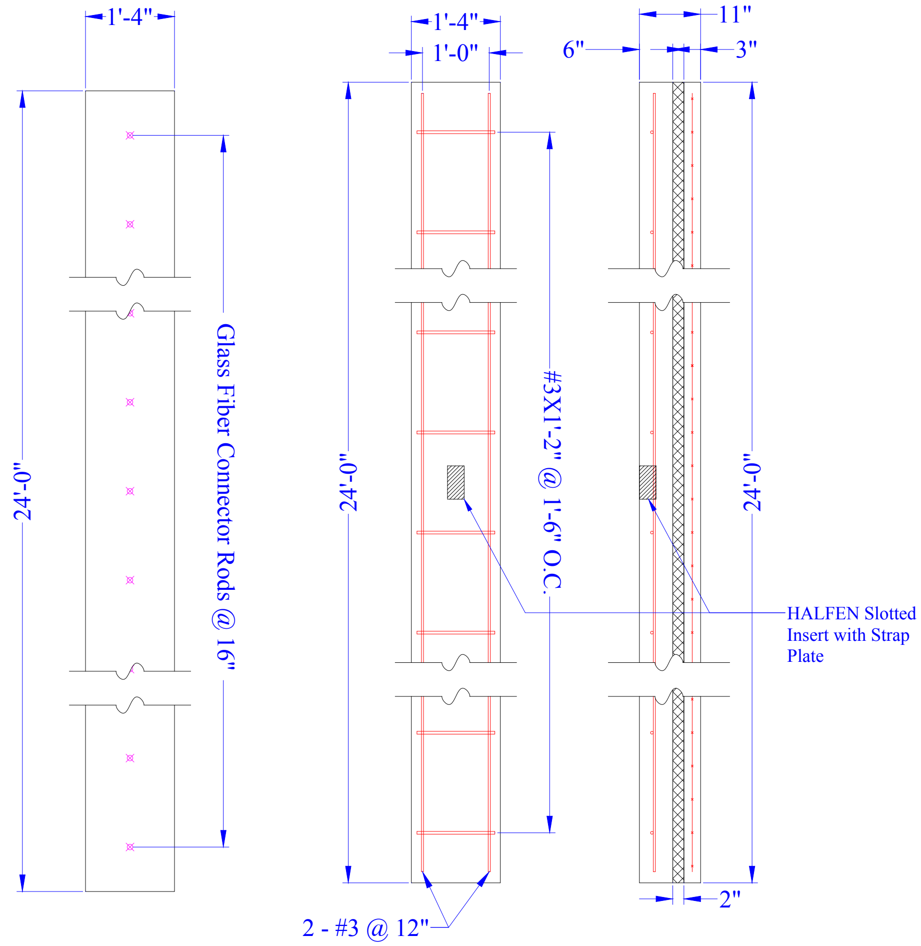


**Figure 181. TS3-A, B Panel Detail**

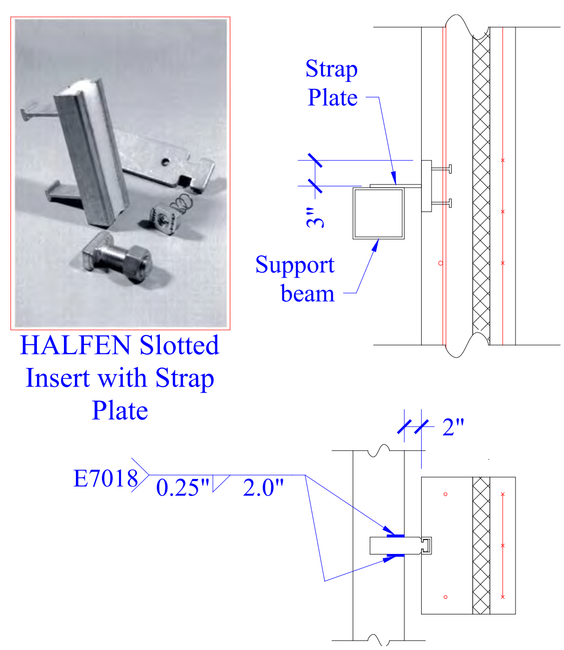


**Figure 182. TS3-A, B Connection Detail**


Distribution Statement A: Approved for public release; distribution unlimited.

The measured response is summarized in Table 36.  The midspan pressure displacement for the two specimen follows in Figure 183.  The individual response of each panel, the end slips, and quarter point displacements are included in Figure 184-186.

**Table 36. TS3-A and B Measured Response**

| Specimen | Age at Test [days] | Max Load [lbs] | Max Pressure [psi] | East Corresponding Displacement [in] | West Corresponding Displacement [in] | East Slip [in] | West Slip [in] | Measured (+) Moment Capacity (9/64$wL^2$) | Measured (-) Moment Capacity (1/4*$wL^2$) |
|---|---|---|---|---|---|---|---|---|---|
| TS3-A | 128 | 14512.3 | 3.335 | 2.573 | 3.403 | 0.243 | 0.119 | 138.8 | 247 |
| TS3-B | 132 | 14210.9 | 3.265 | 1.914 | 2.654 | 0.193 | 0.016 | 135.9 | 242 |
| | Average | 14361.6 | 3.300 | 2.243 | 3.028 | 0.218 | 0.067 | 137 | 244 |

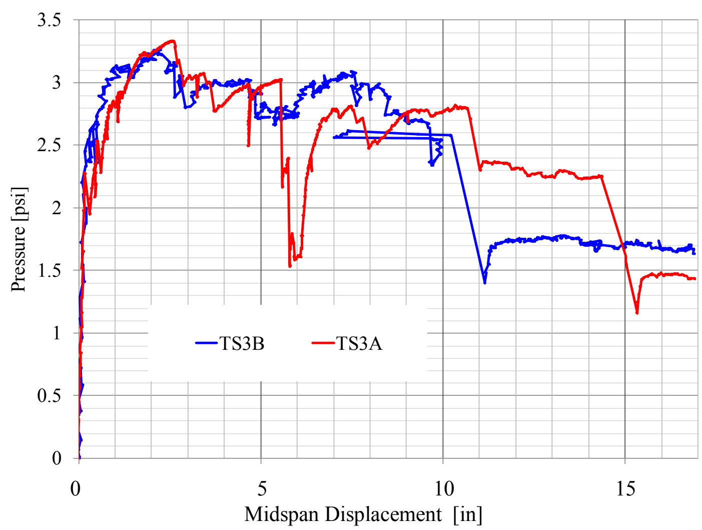


**Figure 183. TS3-A, B Pressure–Displacement Response**

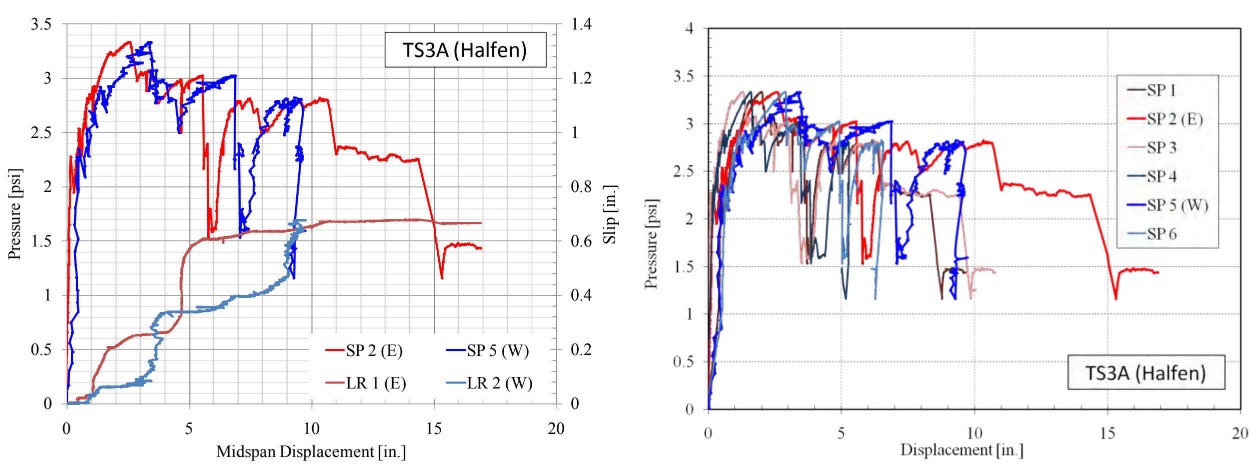


**Figure 184. TS3-A Response**



Distribution Statement A:  Approved for public release; distribution unlimited.

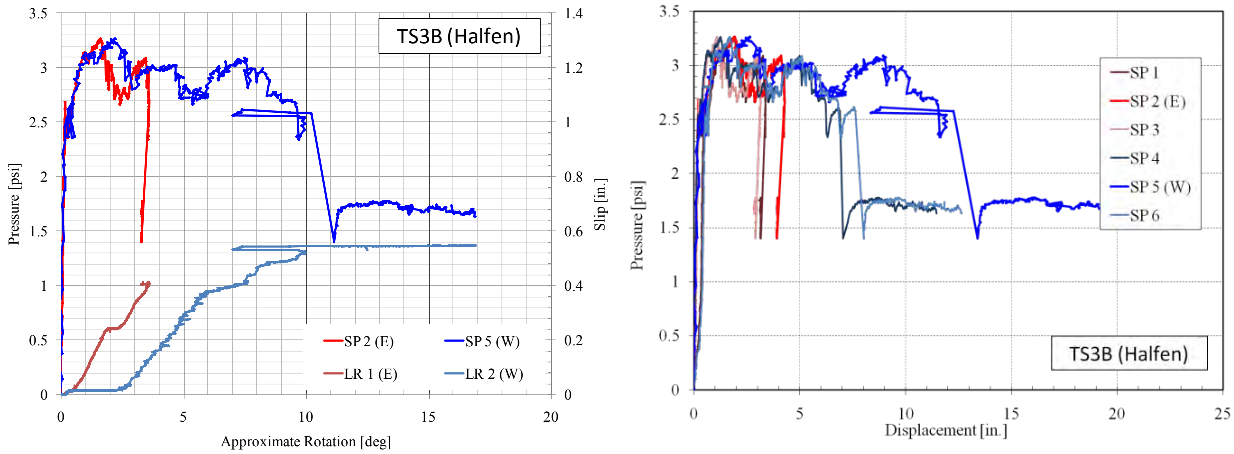


**Figure 185. TS3-B Response**


**Figure 186. TS3 Panel Response (A, B)**

## 8.4. TS3-C and D 6-2-3 Specimen Performance

TS3-C and D consist of a two-span non-composite 6-2-3 PC CSW panel fabricated with XPS insulation and glass fiber THERMOMASS® non-composite shear pins. The panel is non-


Distribution Statement A: Approved for public release; distribution unlimited.

prestressed with rebar transverse reinforcement in the interior wythe and WWR in the exterior wythe. The panel cross-section and reinforcement details are illustrated in Figures 187 and 188. The midspan connection consists of a bearing detail as illustrated in Figure 189.

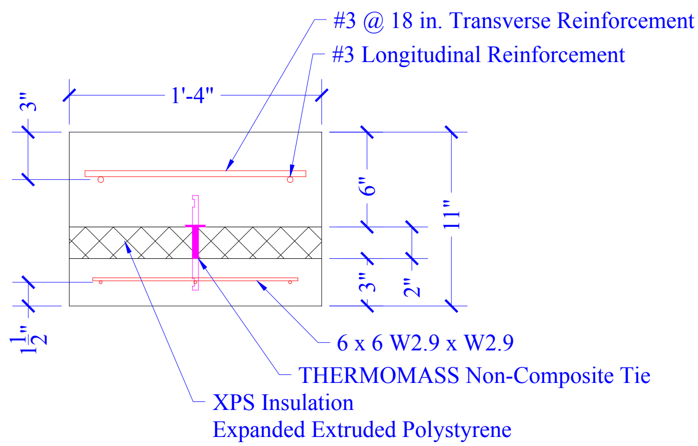


**Figure 187. TS3-C, D Cross-Section Detail**

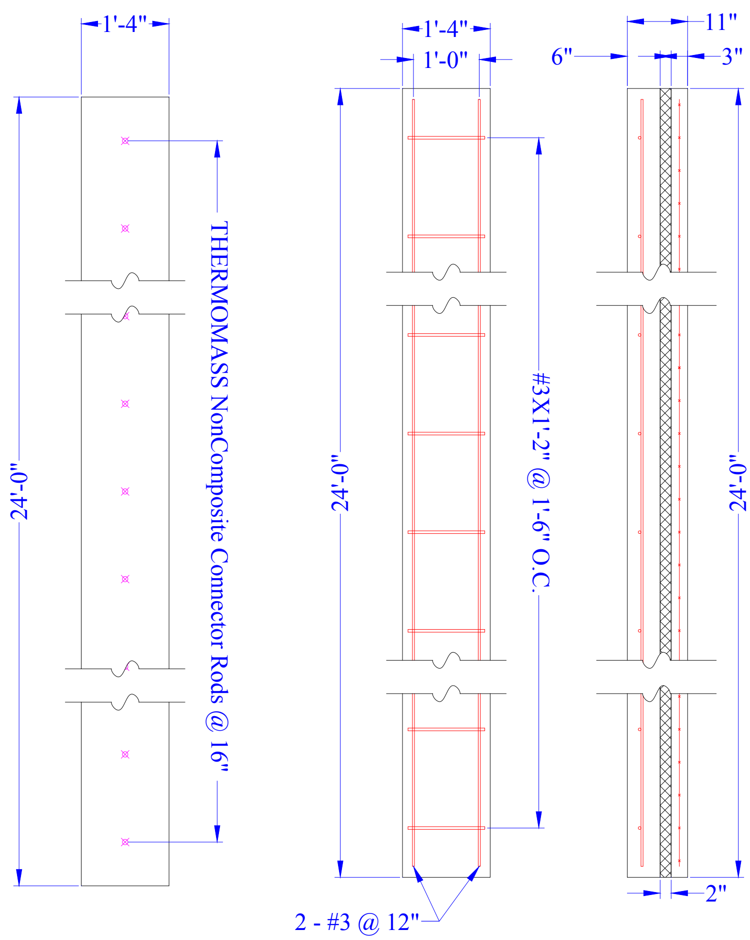


**Figure 188. TS3-C, D Panel Detail**



Distribution Statement A: Approved for public release; distribution unlimited.

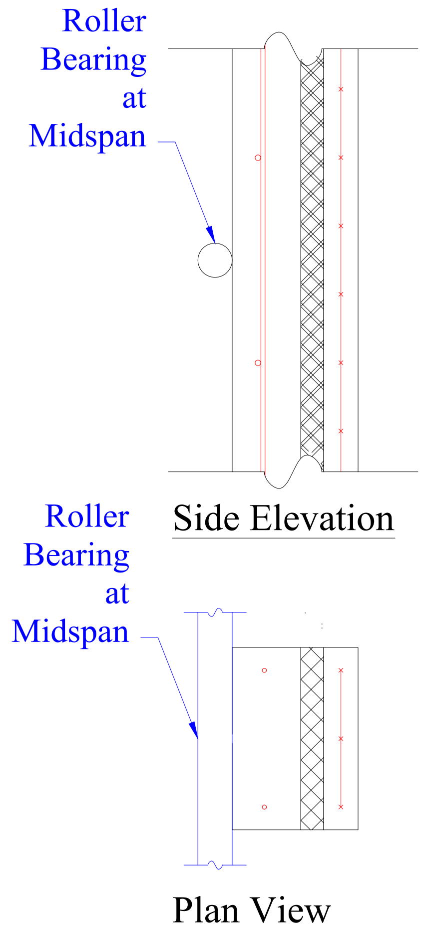


**Figure 189. TS3-C, D Connection Detail**

The measured response is summarized in Table 37. The midspan pressure displacement for the two specimen follows in Figure 190. The individual response of each panel, the end slips, and quarter point displacements are included in Figures 191-193.

**Table 37. TS3-C and D Measured Response**

| Specimen | Age at Test [days] | Max Load [lbs] | Max Pressure [psi] | East Corresponding Displacement [in] | West Corresponding Displacement [in] | East Slip [in] | West Slip [in] | Measured (+) Moment Capacity ($9/64wL^2$) | Measured (-) Moment Capacity ($1/4*wL^2$) |
|---|---|---|---|---|---|---|---|---|---|
| TS3-C | 126 | 12817.2 | 2.945 | 3.591 | 3.984 | 0.273 | 0.663 | 122.6 | 218 |
| TS3-D | 127 | 17073.1 | 3.923 | 2.206 | 2.420 | 0.003 | 0.001 | 163.3 | 290 |
| | Average | 14945.1 | 3.434 | 2.899 | 3.202 | 0.138 | 0.332 | 143 | 254 |


Distribution Statement A: Approved for public release; distribution unlimited.

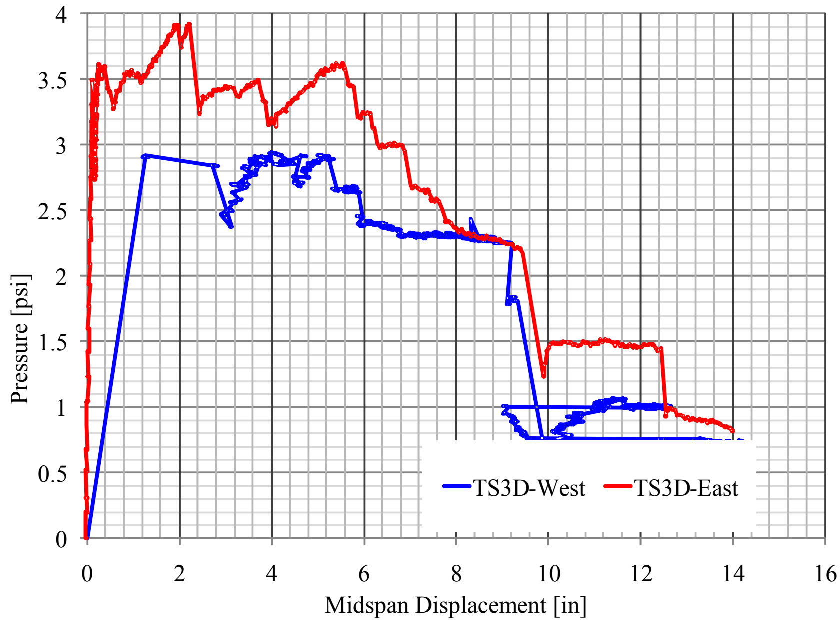


**Figure 190. TS3-C, D Pressure–Displacement Response**

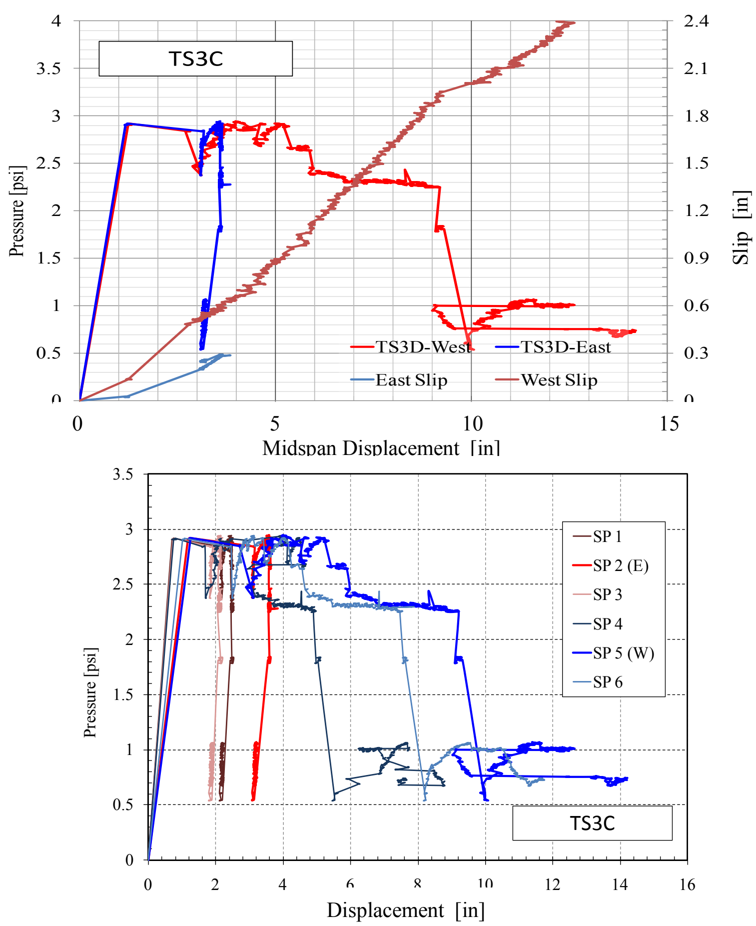


**Figure 191. TS3-C Response**



Distribution Statement A: Approved for public release; distribution unlimited.

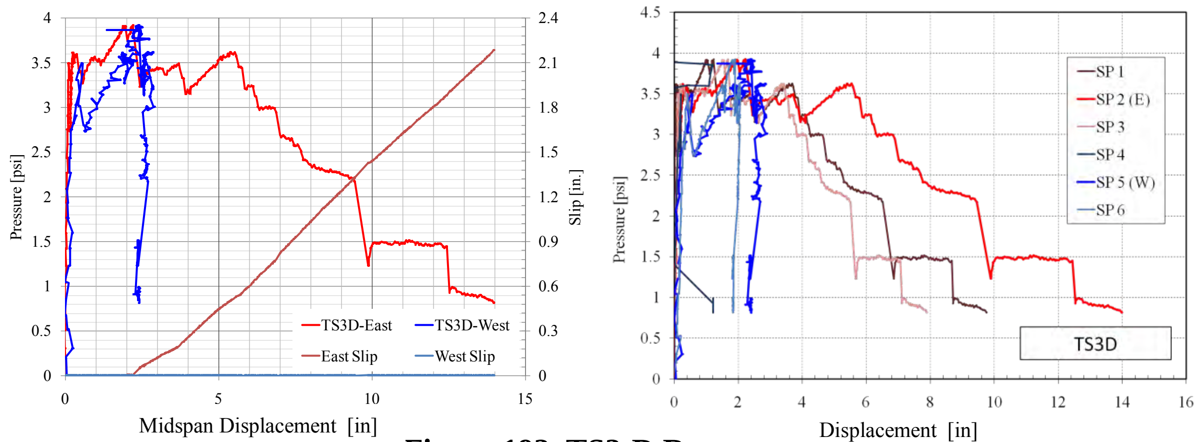


**Figure 192. TS3-D Response**

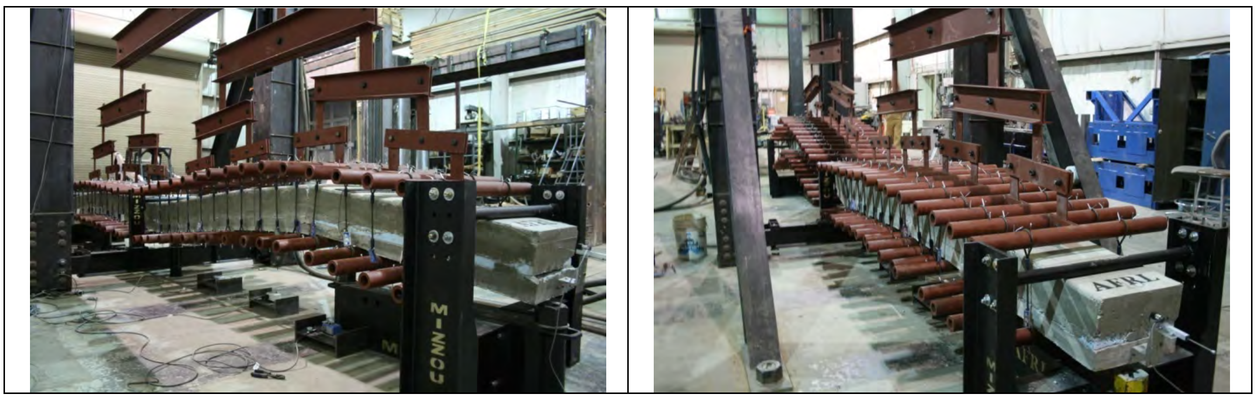

**Figure 193. TS3 Panel Response (C, D)**

## 8.5. TS3-E and F 6-2-3 Specimen Performance

TS3-E and F consist of a two-span non-composite 6-2-3 tilt-up CSW panel fabricated with XPS insulation and glass fiber THERMOMASS® non-composite shear pins. The panel is non-prestressed with rebar transverse reinforcement in the interior wythe and WWR in the exterior wythe. The panel cross-section and reinforcement details are illustrated in Figure 194 and 195. The midspan stud group connection is illustrated in Figure 196.

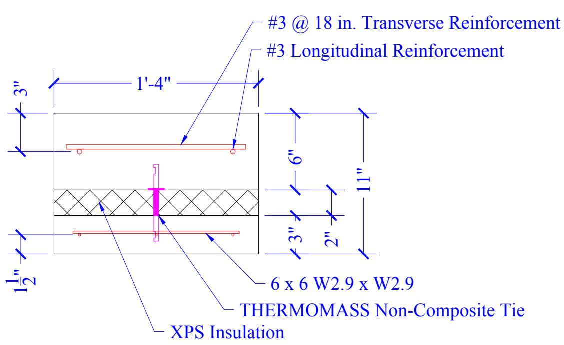


**Figure 194. TS3-E, F Cross-Section Detail**


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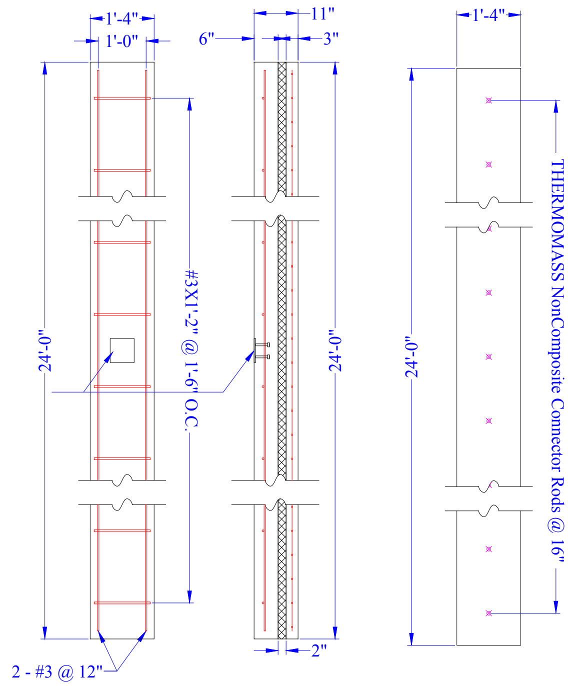


**Figure 195. TS3-E, F Panel Detail**

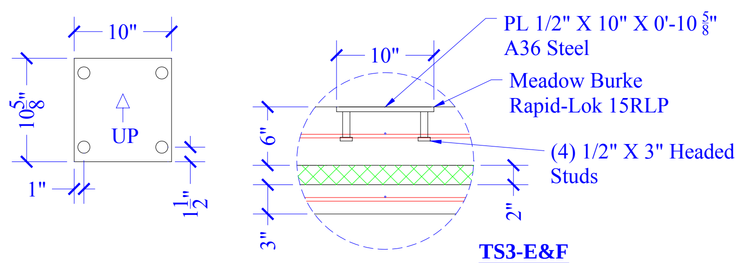


**Figure 196. TS3-E, F Connection Detail**

The measured response is summarized in Table 38. The midspan pressure displacement for the two specimen follows in Figure 197. The individual response of each panel, the end slips, and quarter point displacements are included in Figures 198-200.

**Table 38. TS3-E and F Measured Response**

| Specimen | Age at Test [days] | Max Load [lbs] | Max Pressure [psi] | East Corresponding Displacement [in] | West Corresponding Displacement [in] | East Slip [in] | West Slip [in] | Measured (+) Moment Capacity ($9/64wL^2$) | Measured (-) Moment Capacity ($1/4*wL^2$) |
|---|---|---|---|---|---|---|---|---|---|
| TS3-E | 136 | 13766.5 | 3.163 | 1.669 | 6.572 | 0.191 | 0.738 | 131.6 | 234 |
| TS3-F | 140 | 14363.8 | 3.301 | 1.282 | 2.791 | 0.150 | 0.213 | 137.4 | 244 |
| | Average | 14065.1 | 3.232 | 1.476 | 4.681 | 0.171 | 0.475 | 134 | 239 |


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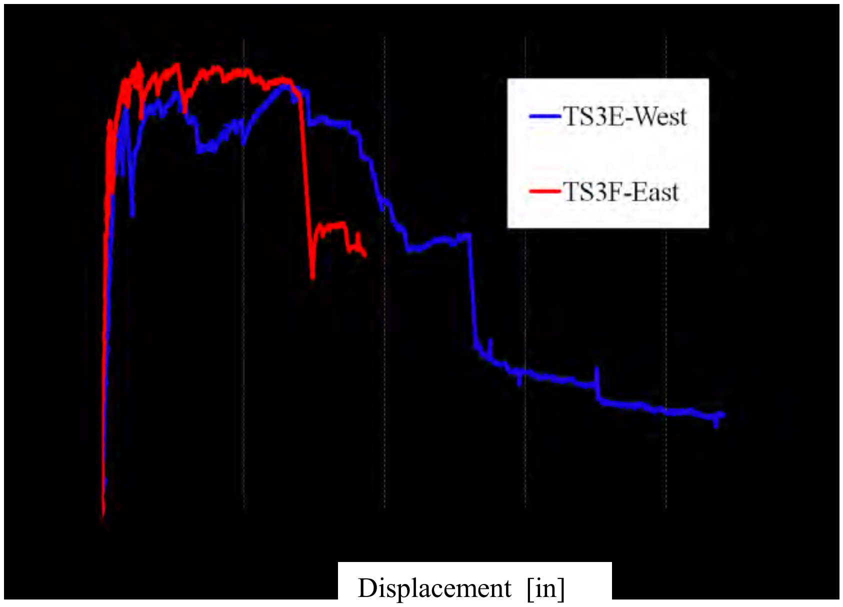

**Figure 197. TS3-E, F Pressure–Displacement Response**

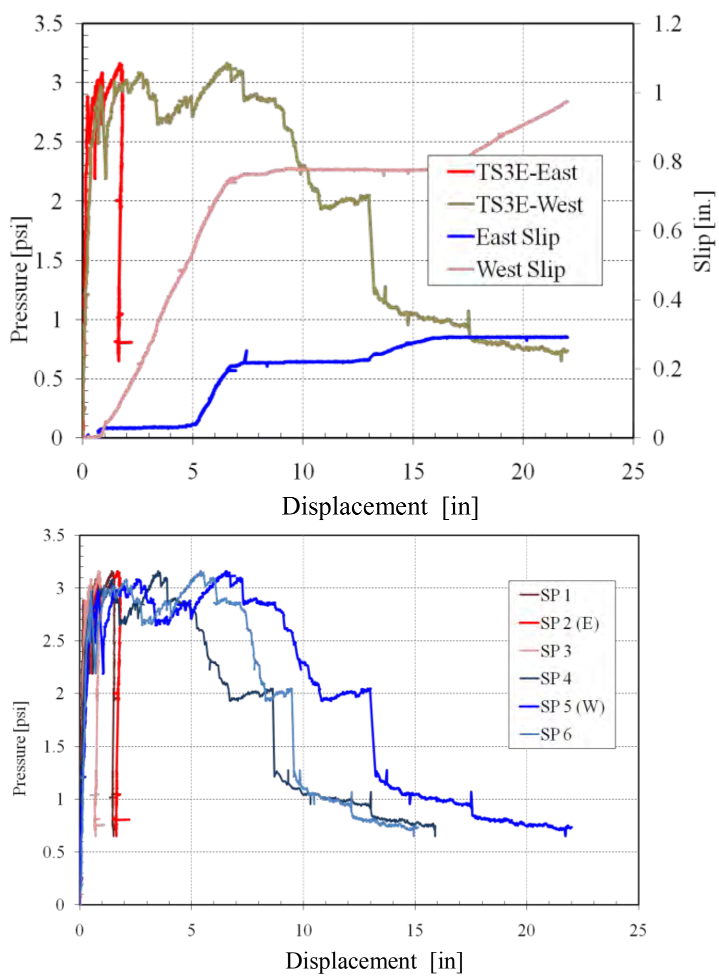

**Figure 198. TS3-E Inbound Response**


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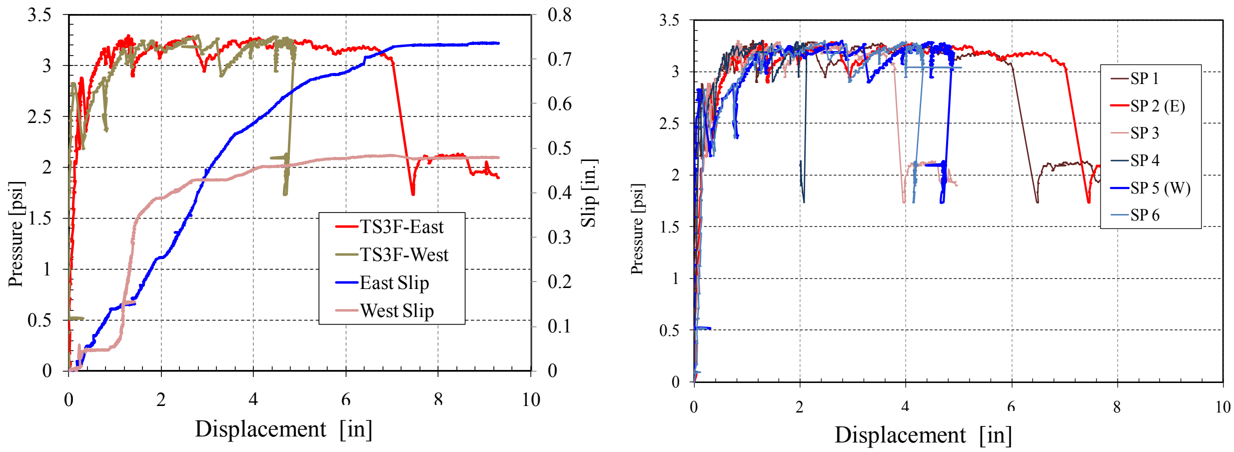


**Figure 199. TS3-F Rebound Response**

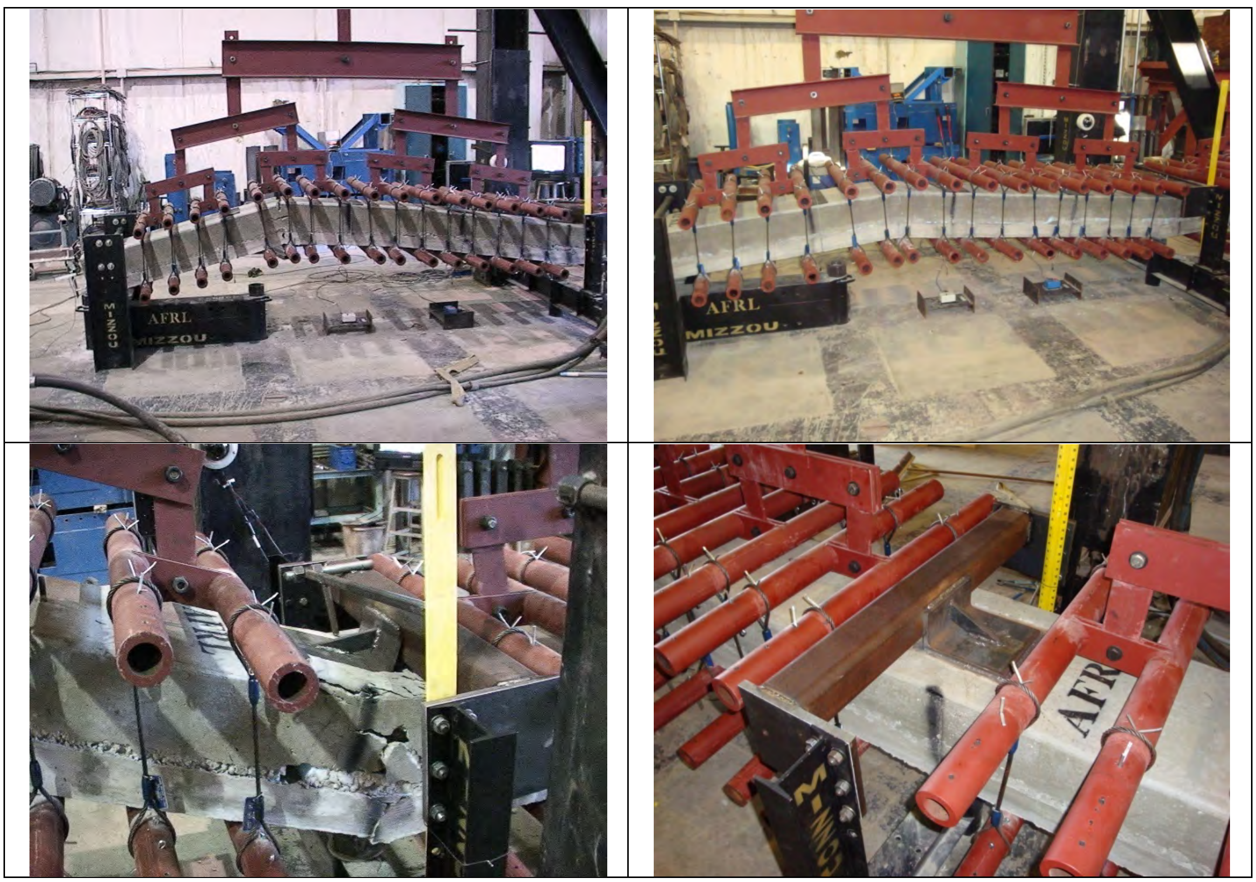


**Figure 200. TS3 Panel Response (E, F)**


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# 9. DISCUSSION OF RESULTS

The results of the static uniform load experiments are examined in this chapter. The results are discussed relative to the single-span, two-span, single-span with end connections, and single-span with unbonded reinforcement.

## 9.1. Single-span Panels

The average response of all the single-span panels without end connections is illustrated in Figures 201-204. The average response from each group of experiments was computed by averaging pressure for each displacement level as illustrated in Figure 205.

Two tilt-up concrete panels were fabricated. TS1, a 6-2-3 panel, was detailed with non-composite shear ties and was designed to have the interior 6-in wythe provide all the flexural strength. Panel TS2, a 3-2-3 panel, was designed with composite shear ties. The composite panel was able to provide greater strength with similar deformation capacity.

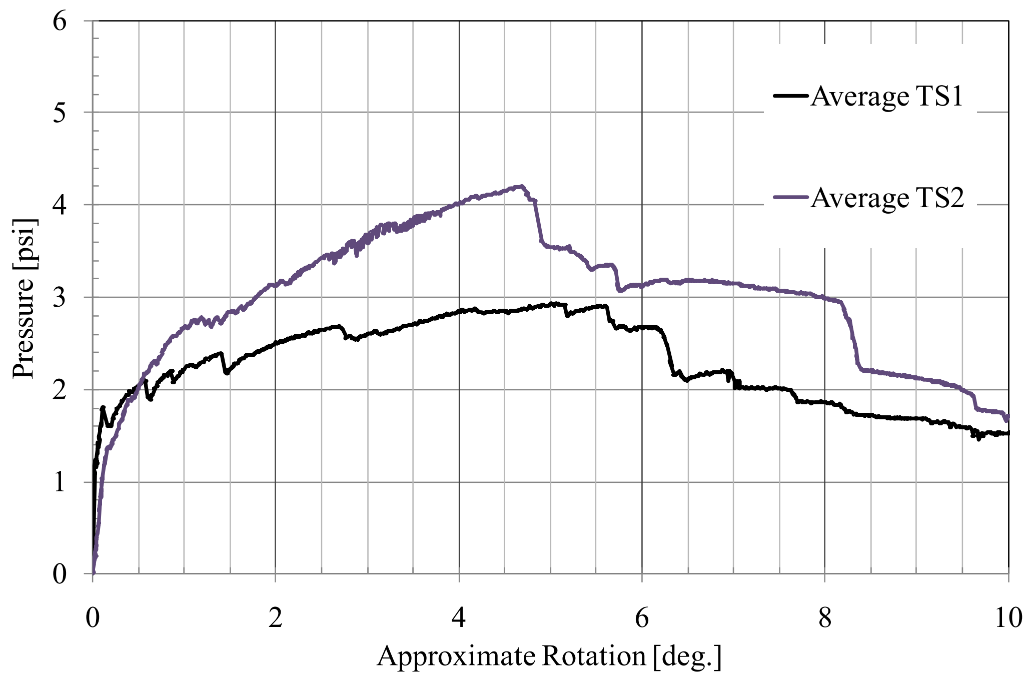


**Figure 201. Average Single-span Tilt-Up Panels**

The 3-2-3 panels are presented in Figure 202. The three panels containing conventional non-prestressed longitudinal reinforcement, TS2, PCS3, and PCS3 (Type2), were capable of achieving support rotations of greater than 4 degrees prior to strength degradation. The prestressed panels PCS1 and PCS2 achieved less ductility than the non-prestressed panels. A comparison of PCS1 and PCS2 shows that the response is sensitive to the tie type used. Both panels contain the same flexural reinforcement. PCS1 uses steel C-clips while PSC2 uses C-Grid®. The C-Grid® has a much greater stiffness than that of the C-clips and consequently softens at a higher pressure level.



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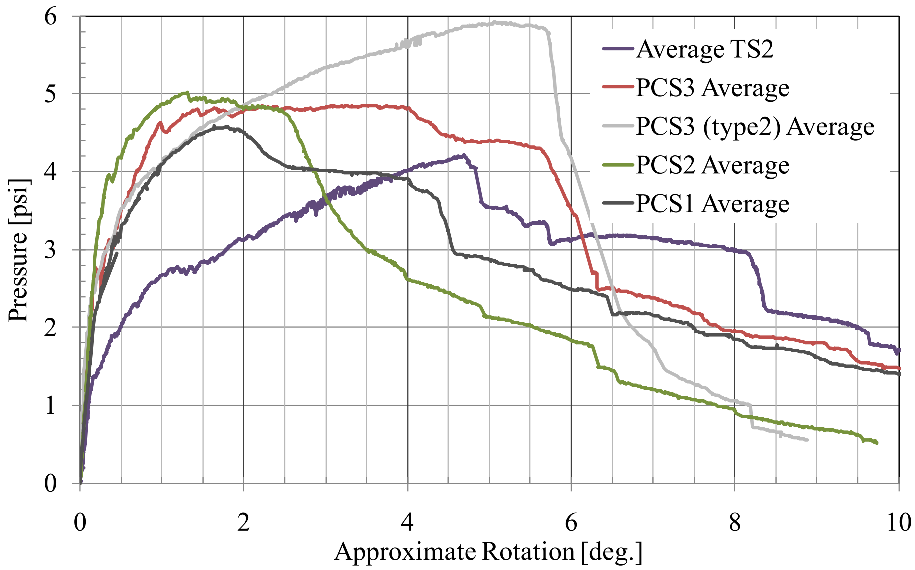


**Figure 202. Average Single-span Response 3-2-3 Panels**

The response of the 3-2-3 panels is sensitive to the shear tie connectors and foam type used, as illustrated in Figure 203. Aside from panel PCS7, all 3-2-3 panels began with the same elastic stiffness. PCS4, 5, and 6 all contain the same flexural reinforcement and XPS insulation. The ties vary and include C-Clips, glass pins, and C-Grid® for PCS4, 5, and 6, respectively. The post-cracking stiffness varies in accordance with the tie stiffness. The C-clip is the least stiff followed by the glass pins, and the C-Grid®. The use of unsealed PIMA insulation significantly increases the early stiffness of the panel over that of XPS insulation. This can be observed when comparing PCS6 to PCS9. The use of one insulating form layer is critical for composite action. PCS8 was fabricated using two layers of PIMA with sealed interface between layers. This break in the insulation resulted in a reduction in strength and stiffness over that of XPS. This can be observed when comparing PCS5 to PCS8.

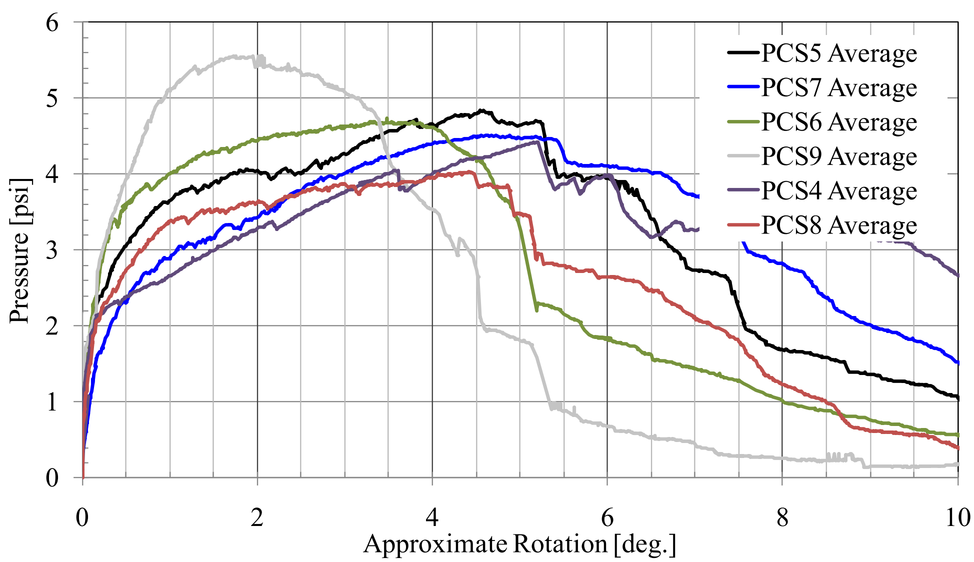


**Figure 203. Average Single-span Response 3-2-3 Panels**


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The use of an unbonded region of prestressing reinforcement was intended to enhance the flexural ductility of the panel. As illustrated, the use of unbonding marginally reduced the flexural stiffness of the panel. The failure modes and strength were not affected. Forensic evaluation of the panels after testing revealed mortar on the unbonded strand. It is likely that the strand was not correctly unbonded in this test series.

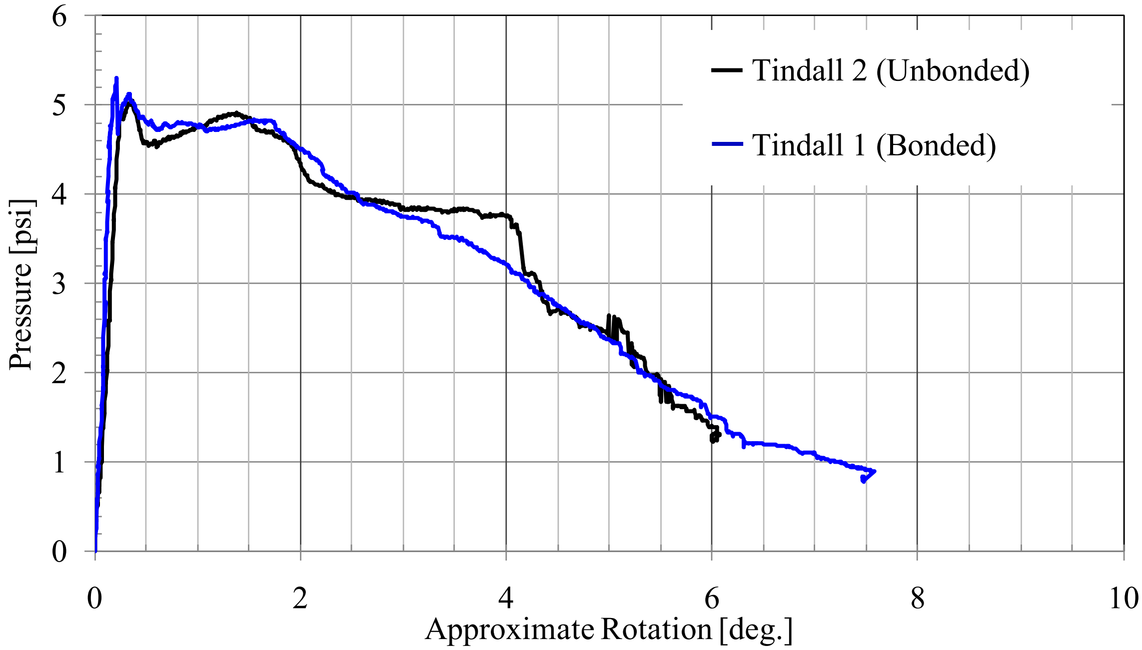


**Figure 204. Average Single-span Response 3-4-3 Panels**

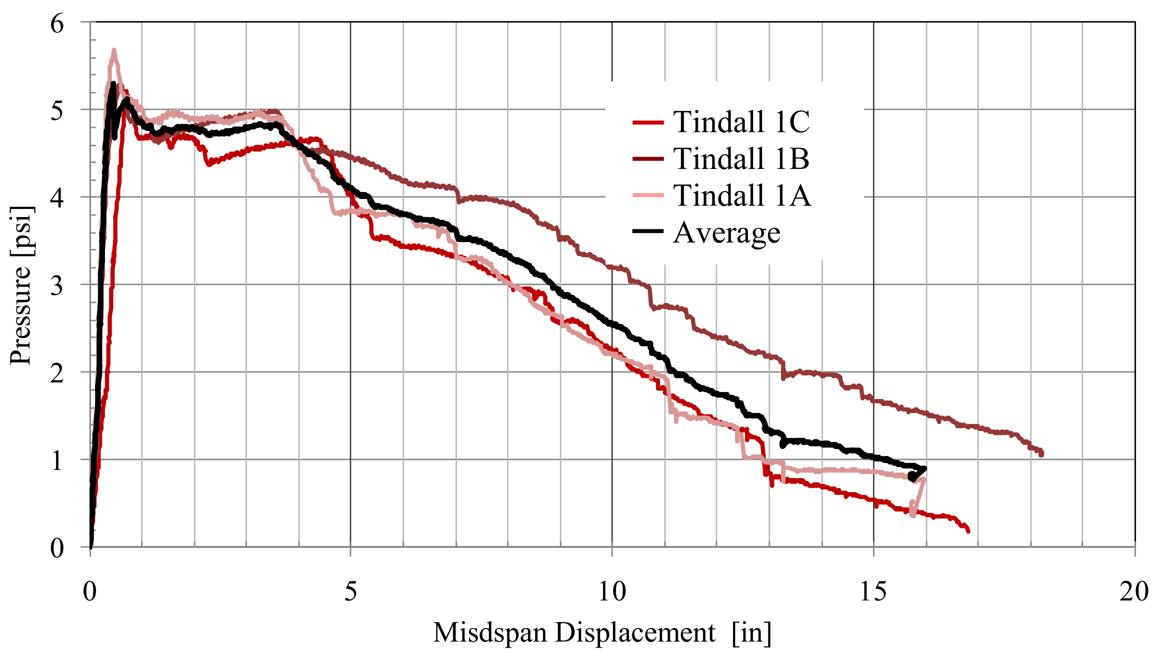


**Figure 205. Average Computation**


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The use of prestressing strand versus conventional non-PS reinforcement is compared in specimens PCS2 and PCS3 (Fig. 206). Both specimens achieved approximately the same flexural strength. The use of non-prestressed reinforcement results in a softening behavior due to cracking. This is not as evident in the PS section (PCS2). The use of PS reduces the deformation ductility by approximately 50%. This inability to support larger deformations supports the lower response limits used for PS elements. The addition of supplemental non-prestressed reinforcement, however, improves the ductility to that of the non-PS case. Therefore, for panels where large rotations are needed, addition of non-PS reinforcement should increase the ductility of the system.

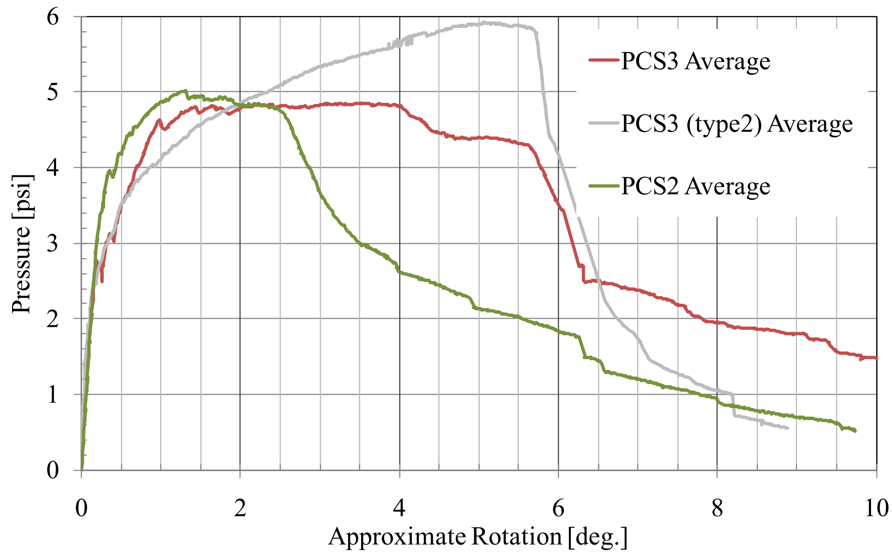


**Figure 206. Prestressed versus Non-PS Reinforcement**

The panel strength is directly related to the foam type used. Panels were fabricated with the same reinforcement but different thickness and type of foam. A 3-2-3 and a 3-3-3 panel were tested with the same reinforcement. Based on composite action, the 3-3-3 panel should provide a higher moment capacity than that of the 3-2-3 panel due to the larger moment arm. The two panels, however, achieved approximately the same strength. This can be observed when comparing PCS1 to PCS4 and PCS2 to PCS6 (Fig. 207). In both cases the use of XPS (over EPS) insulation resulted in a softer post-cracking stiffness, larger ductility, and lower strength (even with the larger moment arm). The use of PIMA increased the strength of the panels further. This can be observed when comparing PCS6 to PCS9. It is noted that both the EPS and PIMA have a rough absorbent surface compared to the XPS insulation, which is smooth and sealed. The additional roughness provided additional horizontal shear strength against flexural demands. The THERMOMASS® panels exhibited the opposite behavior. The use of PIMA resulted in a decrease in strength over the XPS panel. The reason for this decrease is due to the fact that two 1.5-in thick PIMA sheets were used to make up the 3-in foam thickness needed in PCS8. This created a slip plane in the insulation thus reducing the shear strength.

Based on these results, the use of rough absorbent insulation foam can be used to increase the post-cracking stiffness and flexural strength of a panel. The use of multiple layers of foam or XPS foam will reduce these effects, but will typically allow more deformation prior to failure.


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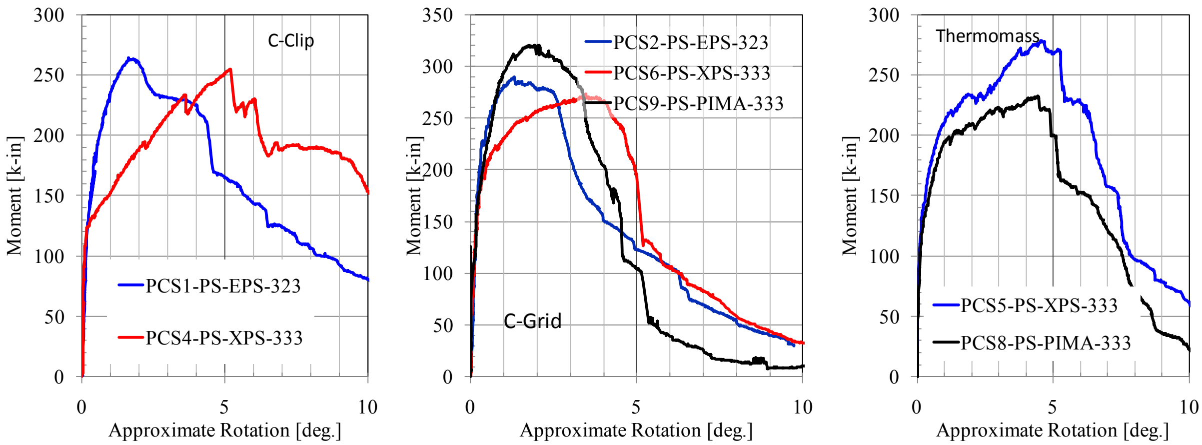


**Figure 207. Influence of Foam**

The panel capacity was estimated using two methods. The first method was performed in accordance with ACI 318 flexural strength formulations, and the second method used strain compatibility. All longitudinal reinforcement was accounted for in the strength estimates. The as-built dimensions of the reinforcement were used for the estimates. The ACI formulation followed a popular method of simplification. The reinforcement in both wythes was lumped at a centroid location. The total area of steel and the associated moment arm were used. The strain compatibility analysis method accounted for the doubly reinforced geometry of the section. The estimated capacities are compared to the measured capacities in Table 39.

The panels range from a low of 36% composite to 134% composite with an average of 71% composite. In general the panels were not able to reach their estimated composite flexural strength. Only the tilt-up 3-2-3 panel TS2 and reinforced concrete PCI type panel with non-PS reinforcement and C-Grid® PCS3 were able to exceed their estimated composite strength. The other panels behaved partially composite.

### 9.1.1. Backbone Estimation of Response

To compare the results of the static experiments to the current response limits, the results were simplified into a backbone or multi-linear resistance function. Backbones are an approximate representation of the relationship between two variables. Whereas some methods of empirical characterization tend to focus on one variable—e.g., yield point through offset yield method—backbones attempt to capture an entire response. Figure 208 shows the backbones developed from the measured responses for one set of single-span panels. Note that the variability between PCS3 specimens is large and is not typical of the other samples.


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## Table 39. Strength Estimates

| Specimen | Wythe Configuration | Insulation | Panel Reinforcement | Composite Ties | Average Measured Moment Capacity | Estimated Composite Capacity | | Estimated Non-Composite Capacity | | % Composite | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Strain Compat. | ACI 318 | Strain Compat. | ACI 318 | Strain Compat. | ACI 318 |
| TS1 | 6-2-3 | XPS | R.C. | THERMOMASS ® - NC | 89.4 | 110.7 | 110.7 | 42.4 | 41.8 | 69% | 69% |
| TS2 | 3-2-3 | XPS | R. C. | THERMOMASS ® - Comp | 121.3 | 99.8 | 99.8 | 36.1 | 33.5 | 134% | 132% |
| PCS1 | 3-2-3 | EPS | PS/WWR | Steel C-clips | 259.1 | 342 | 335 | 122 | 103 | 62% | 67% |
| PCS2 | 3-2-3 | EPS | PS/WWR | C-Grid® | 294.8 | 337.6 | 326.5 | 113.4 | 94.8 | 81% | 86% |
| PCS3 | 3-2-3 | EPS | Rebar/WWR | C-Grid® | 306.1 | 275.5 | 275.5 | 89.7 | 83.2 | 116% | 116% |
| PCS4 | 3-3-3 | XPS | PS/Rebar | Galvanized Steel C-clips | 268.3 | 379.3 | 368.7 | 114.5 | 97 | 58% | 63% |
| PCS5 | 3-3-3 | XPS | PS/Rebar | THERMOMASS ® - Comp | 279.7 | 369 | 358.8 | 104.3 | 87 | 66% | 71% |
| PCS6 | 3-3-3 | XPS | PS/WWR | C-Grid® | 249.8 | 393.6 | 382.8 | 121.9 | 103.5 | 47% | 52% |
| PCS7 | 3-3-3 | XPS | Rebar | THERMOMASS ® - Comp | 268.5 | 310.3 | 310.3 | 92.8 | 87.1 | 81% | 81% |
| PCS8 | 3-3-3 | PIMA | PS/Rebar | THERMOMASS ® - Comp | 231.6 | 365.3 | 355.4 | 100.7 | 83.5 | 49% | 54% |
| PCS9 | 3-3-3 | PIMA | PS/WWR | C-Grid® | 322.9 | 398.2 | 387.4 | 126.5 | 107.9 | 72% | 77% |
| PCS10 | 3-3-3 | XEPS 1# | PS/WWR | C-Grid® | 275.9 | 388.1 | 377.2 | 115.7 | 97.4 | 59% | 64% |
| PCS11 | 3-3-3 | XEPS 1# | PS/WWR | C-Grid® | 307.5 | 407.2 | 397.7 | 134.6 | 117.9 | 63% | 68% |
| PCS3 (T2) | 3-2-3 | EPS | PS&Rebar/WWR | C-Grid® | 332.4 | 573.9 | 578.1 | 196.6 | 153.4 | 36% | 42% |

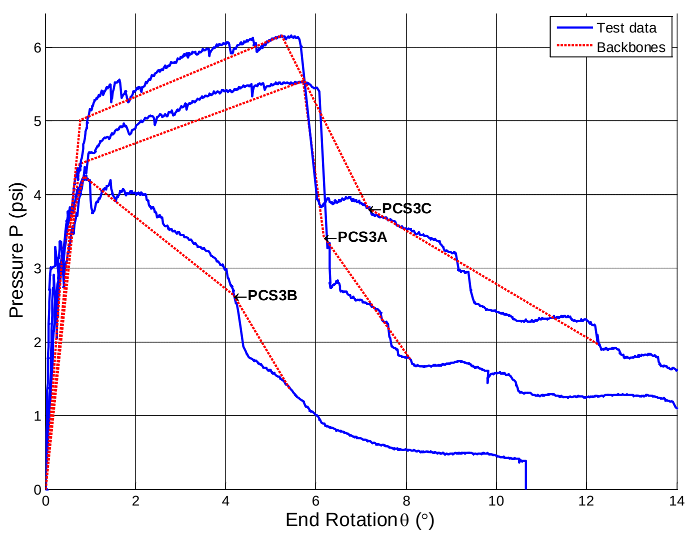


**Figure 208. Pressure–Rotation Characterization (1 psi = 6.9kPa)**



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A four-point backbone of each experiment was developed (Fig. 209) and used to quantify the average response of the PS and reinforced concrete specimens. A procedure was developed to minimize the error between the energy of the measured performance and that of the backbone. Seven points are used to characterize the response: K, L, L0, L1, M, S, and T. Point M corresponds to the maximum pressure and corresponding rotation response, θ. K represents a point on the response in the elastic range. L0 represents the point where a secant through point K intersects the maximum pressure. Point L1 represents the point on the response at the same rotation level as point L0. Point L represents the intersection of the lines formed from the secant through point K and the line formed between point M and L1. Points S and T represent the descending branch of the response. The points K, S, and T were chosen as a percentage of $P_{max}$ that would minimize the error between the measured pressure–rotation response and the final backbone. The error was computed as shown in Equation 3.

$$\text{error} = \frac{\int P\Delta d\Delta(\text{actual}) - \int P\Delta d\Delta(\text{backbone})}{\int P\Delta d\Delta(\text{actual})} \qquad (3)$$

Values for K, S, and T were determined as 64% $P_{max}$, 62% $P_{max}$, and 32% $P_{max}$, respectively. These values provide the lowest average error on the entire dataset of one-span panel tests. A sample backbone for specimen PCS5-C using these limits is illustrated in Figure 210.

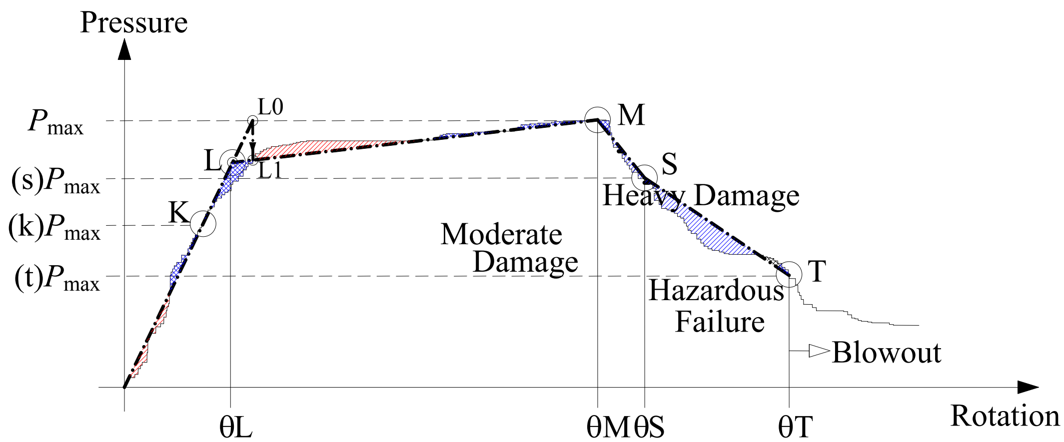


**Figure 209. Backbone Development**

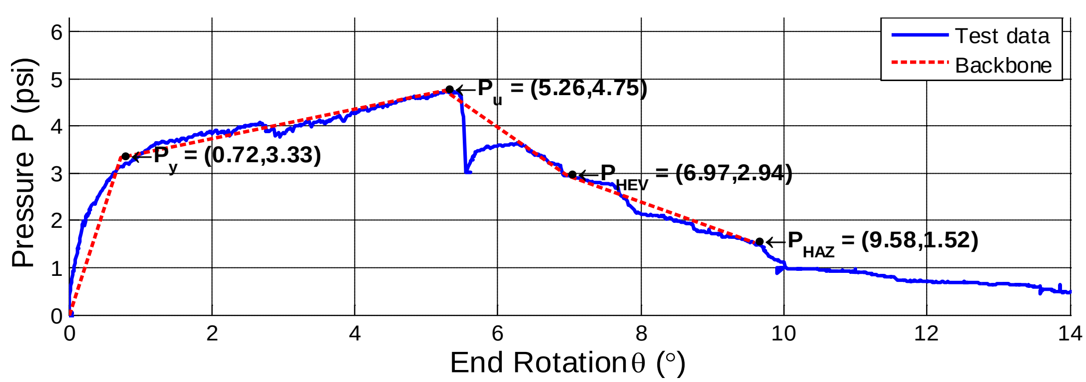


**Figure 210. Backbone with Optimum Constants (1 psi = 6.9 kPa)**



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The backbone response was used to divide the panel response into different component damage levels. The division between superficial and moderate damage was not changed from the current recommendation of a ductility of 1.0. At the end of the superficial damage range, yielding initiates. Any damage prior to reinforcement yielding will be cosmetic in nature. The panels form a stable flexural response up to their ultimate capacity. Just past the ultimate strength, a flexural hinge occurs near midspan. The maximum load is used as the division between moderate and heavy damage. Heavy damage corresponds to the range from $P_{max}$ to a decrease in the strength of 62% of $P_{max}$. Hazardous damage ranges from 62% $P_{max}$ to 32% $P_{max}$. Blowout was assumed to occur at a strength of less than 32% of $P_{max}$.

The backbone response of each panel was averaged by type and is presented in Table 40. The end rotation for each backbone level (L, M, S, and T) for both the RC and PS concrete samples are summarized along with the average maximum pressure for each configuration. The results are sorted with respect to the construction type (RC or PS) and the end rotation at maximum pressure. The backbones for the reinforced and PS sandwich panels are shown graphically in Figure 211 and Figure 212, respectively.

**Table 40. Average Backbone Response of Single-span Panels**

| Panel ID | $P_{max}$ [psi] | Backbone rotation limits for damage levels [degrees] | | | |
|---|---|---|---|---|---|
| | | θL | θM | θS | θT |
| PCS7 (RC) | 4.64 | 1.1 | 5.8 | 7.6 | 9.8 |
| TS1 (RC) | 2.79 | 0.4 | 5.5 | 7.8 | 12.0 |
| TS2 (RC) | 4.21 | 1.0 | 5.0 | 8.7 | 10.7 |
| PCS3 (RC) | 5.31 | 0.6 | 3.9 | 5.8 | 8.6 |
| PCS4 (PS) | 4.66 | 1.7 | 5.9 | 9.0 | 15.9 |
| PCS5 (PS) | 4.85 | 0.7 | 4.9 | 7.0 | 8.5 |
| PCS3 (Type 2) (PS) | 5.77 | 0.9 | 4.6 | 5.6 | 6.3 |
| PCS8 (PS) | 4.16 | 0.5 | 4.6 | 6.4 | 7.6 |
| PCS6 (PS) | 4.30 | 0.3 | 2.7 | 4.6 | 6.7 |
| PCS9 (PS) | 5.60 | 0.5 | 2.0 | 4.0 | 4.7 |
| PCS2 (PS) | 5.11 | 0.2 | 1.8 | 3.3 | 6.2 |
| PCS1 (PS) | 4.47 | 0.4 | 1.7 | 5.2 | 11.9 |
| Note: 1 psi = 6.9 kPa | | | | | |

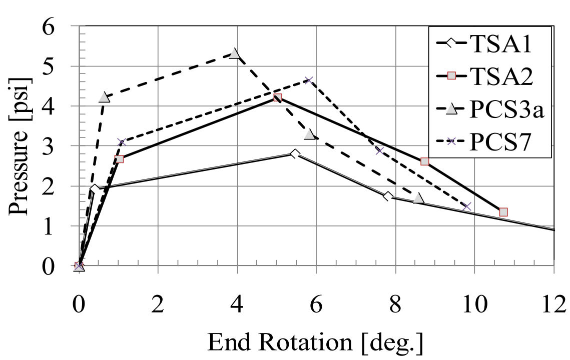


**Figure 211. Reinforced Backbones**

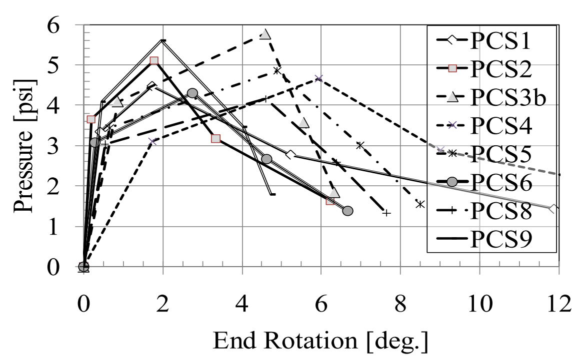


**Figure 212. Prestressed Backbones**



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The 12 individual RC and 24 individual PS panel rotations were averaged to determine the general response limits of the insulated panels. The averages and standard deviations are summarized in Table 41 along with the current US Army response limitations [US Army 2008]. Recommended limits are developed for the RC and PS insulated sandwich panels based on Equation 4. Due to the small sample size the proposed response limits are reduced from the average rotation levels. The proposed limits are based on a *Z*-distribution with a 90% confidence level. (*AVE* is the average and *SD* is the standard deviation.)

$$\theta \leq AVE - 1.28 \text{ x } SD \quad (4)$$

**Table 41. Average Rotation Capacity and Proposed Limits**

| | Superficial | Moderate | Heavy | Hazardous | Blowout |
|---|---|---|---|---|---|
| RC Flexural Limit | $\mu \leq 1.0$ | $\theta \leq 2.0^{o}$ | $2.0^{o} < \theta \leq 5.0^{o}$ | $5.0^{o} < \theta \leq 10.0^{o}$ | $\theta > 10.0^{o}$ |
| RC Panel Response (*AVE* ± *SD*) | 0.78º ± 0.34 | 5.06º ± 1.51 | 7.50º ± 1.44 | 10.29º ± 2.12 | - |
| Recommended RC Panel Limit | $\mu \leq 1.0$ | $\theta \leq 3.1^{o}$ | $3.1^{o} < \theta \leq 5.7^{o}$ | $5.7^{o} < \theta \leq 7.6$ | $\theta > 7.6$ |
| PS Flexural Limit | $\mu \leq 1.0$ | $\theta \leq 1.0^{o}$ | $1.0^{o} < \theta \leq 2.0^{o}$ | $2.0^{o} < \theta \leq 3.0^{o}$ | $\theta > 3.0^{o}$ |
| PS Panel Response (*AVE* ± *SD*) | 0.65º ± 0.55 | 3.48º ± 1.67 | 5.61º ± 1.96 | 8.53º ± 3.84 | - |
| Recommended PS Panel Limit | $\mu \leq 1.0$ | $\theta \leq 1.3^{o}$ | $1.3^{o} < \theta \leq 3.1^{o}$ | $3.1^{o} < \theta \leq 3.6^{o}$ | $\theta > 3.6^{o}$ |

### 9.1.2. Estimation of Yield in Sandwich Wall Panels

Building structures with a High Level of Protection criterion are required to limit any damage of the exterior wall panels to superficial. This level of damage is defined as a ductility level of 1.0. Proper determination of this ductility level is critical for effective design of the wall element. The decision to use a lower bound or upper bound estimate of the wall will result in a high or moderate level of reinforcement, respectively.

Current U.S. Army approaches for determining yield deformations of flexural members are based on computation of an effective moment of inertia. The effective moment of inertia is based on an average of the cracked and gross moment of inertia of the panel. The yield deformation, $\Delta_y$, is based on the intersection of the elastic stiffness, $E_c$, using the effective inertia, $I_e$, the flexural strength of the panel, $w_y$ and the span length of the panel, $L$. The formulation follows in Equation 5.

$$\Delta_y = \frac{5 w_y L^4}{384 E_c I_e} \quad (5)$$

$$I_e = \frac{I_{gross} + I_{cracked}}{2} \quad (6)$$

Using this methodology, the yield displacement was computed for the as-built section using the average reinforcement measured from each specimen. The displacements were computed for the


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assumption of full composite action and for the case of non-composite action. The predicted yield displacements are compared to the measured yield displacements in Table 42. The measured yield displacement correspond to the rotation point θL previously defined in Table 40.

The measured yield displacements are bounded by the composite and non-composite deflection predictions. In all cases, using the composite displacement predictions results in an underprediction of the actual displacement. Using the composite deformation prediction for the panels examined resulted in lower-bound estimate of deformation.

**Table 42. Estimated and Actual Deformations**

| Specimen | Measured Yield Displacement [in] | Estimated Displacement [in] | | Percent of Measured | |
|---|---|---|---|---|---|
| | | Composite | Non-Composite | Composite | Non-Composite |
| TS1 (RC) | 0.409 | 0.047 | 0.247 | 12% | 60% |
| TS2 (RC) | 1.061 | 0.103 | 0.961 | 10% | 91% |
| PCS3 (RC) | 0.669 | 0.111 | 1.447 | 17% | 216% |
| PCS7 (RC) | 1.134 | 0.086 | 1.129 | 8% | 100% |
| PCS1 | 0.432 | 0.144 | 1.345 | 33% | 311% |
| PCS2 | 0.201 | 0.141 | 1.318 | 70% | 655% |
| PCS3 (Type 2) | 0.903 | 0.220 | 2.092 | 24% | 232% |
| PCS4 | 1.821 | 0.111 | 1.447 | 6% | 80% |
| PCS5 | 0.687 | 0.108 | 1.414 | 16% | 206% |
| PCS6 | 0.305 | 0.116 | 1.508 | 38% | 495% |
| PCS8 | 0.561 | 0.107 | 1.400 | 19% | 250% |
| PCS9 | 0.475 | 0.117 | 1.528 | 25% | 322% |

## 9.2. Multi-span Panels

The multi-span panels are compared in this section. The responses from the tests are averaged and backbones are created in a similar manner to that of the single-span panels. Sections of the panels are presented again in Figure 213. The pressure versus deformation of the panels are presented in Figure 214 and the simplified backbones are illustrated in Figure 215.

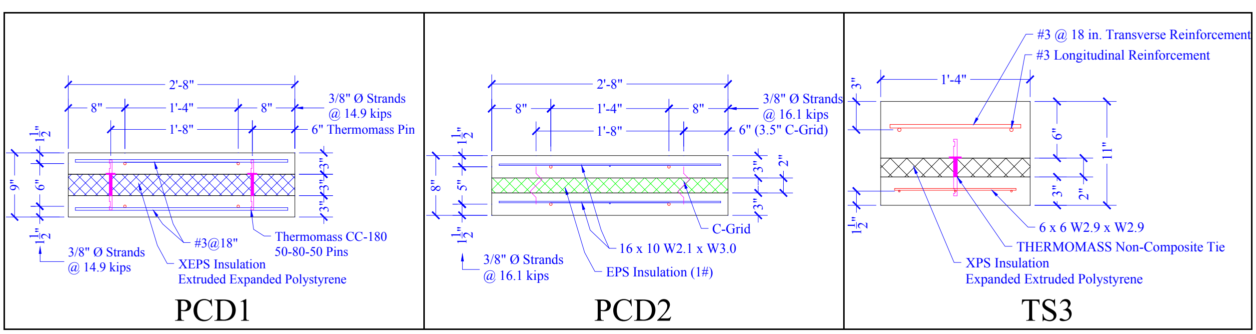


**Figure 213. Two-span Sections**



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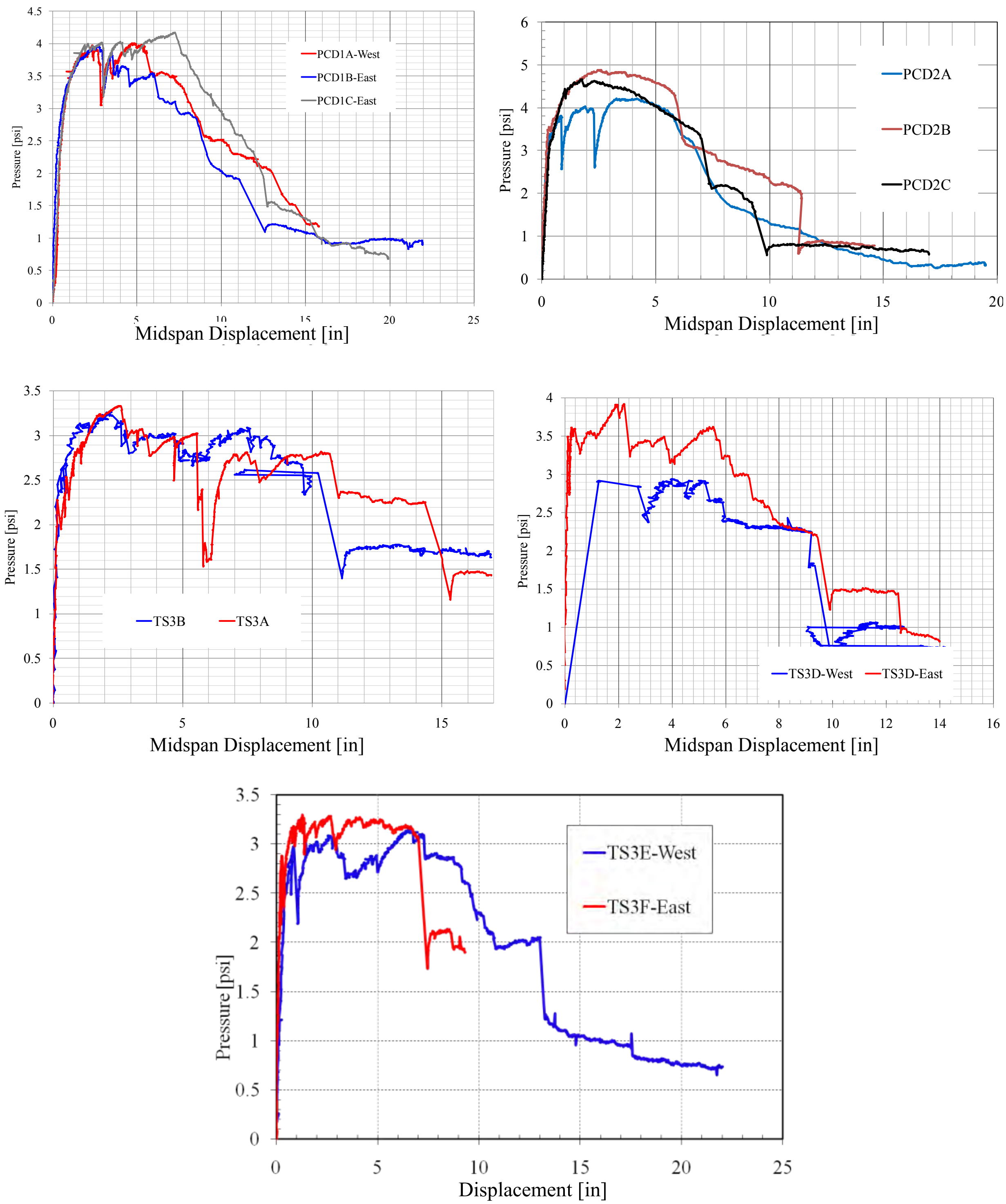


**Figure 214. Measured Responses**


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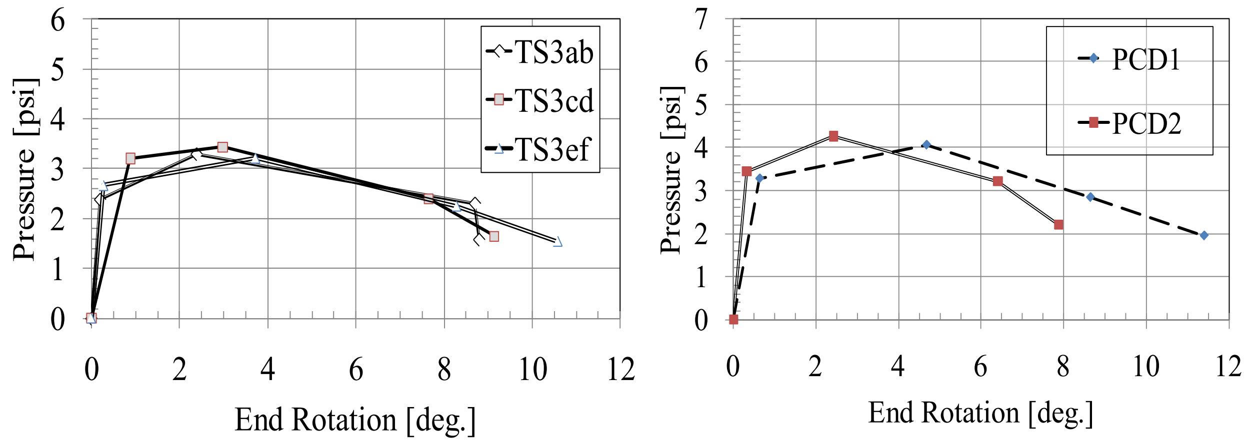


**Figure 215. Backbone Curves**

The average end rotations are presented for the two-span panels. The rotations are computed using the midspan deformations. As illustrated in Table 43, the multi-span panel rotations are on the same order as that of the single-span. The only exception is RC panel TS3, which has a lower rotational limit for the moderate damage level than the single-span, 2 degrees for TS3 versus 5 degrees for TS1. (The moderate damage is the rotation from θL to θM.) The sample size of experiments for the multi-span panels is too small to make generalized conclusions about the response of the system.

Observation of the damage to the multi-span systems revealed connection failures to the panels. For composite panels with 3-2-3 wythe arrangement, the mid-height connections punched through the interior concrete wythe. The connection regions were not reinforced with any special detailing. Due to the negative moment demands at the region, the connection zone was subjected to multi-directional compression. In addition, the flexure produced cracking. The combination of these demands and the lack of crossing reinforcement resulted in the punching failures observed. The 6-2-3 panels did not exhibit punching failures.

**Table 43. Multi-span Panel Response**

| Panel ID | $P_{max}$ [psi] | Backbone rotation limits for damage levels [degrees] | | | |
|---|---|---|---|---|---|
| | | θL | θM | θS | θT |
| PCD1 (PS) | 4.06 | 0.63 | 4.68 | 8.65 | 11.41 |
| PCD2 (PS) | 4.26 | 0.32 | 2.42 | 6.40 | 7.88 |
| TS3-A, B (RC) | 3.30 | 0.20 | 2.38 | 8.69 | 8.79 |
| TS3-C, D (RC) | 3.43 | 0.88 | 2.98 | 7.64 | 9.14 |
| TS3-E, F (RC) | 3.22 | 0.28 | 3.72 | 8.29 | 10.58 |


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## 10. CONCLUSIONS AND FUTURE WORK

An experimental study of insulated CSW panels was conducted to assess performance under a pseudo-blast loading. Wall panels typical of current U.S. construction were fabricated and subjected to a monotonically increasing uniform load until failure. The resistance, deformation and failure characteristics were recorded and discussed in the preceding sections. Both single-span and multi-span panels with typical embedded connections were examined. Based on the results of the research program the following conclusions can be made:

- PS and non-PS concrete wall panels were shown to provide a ductile response when subjected to uniform loading.
- Non-PS panels provide greater ductility than PS panels.
- The addition of non-PS reinforcement to a PS panel allows the panel to achieve ductility levels of non-PS members.
- The shear ties used in the panel affect the flexural response of the system. Specifically, the use of stiff truss type ties results in a stiff flexural response, whereas the use of flexible C-clip ties results in more appreciable softening of the flexural response after cracking.
- Rough absorbent insulation foam can be used to increase the post-cracking stiffness and flexural strength of a panel. The use of multiple layers of foam or XPS foam will reduce these effects but will typically allow more deformation prior to failure.
- The panels range from a low of 36% composite to 134% composite with an average of 71% composite. In general, the panels were not able to reach their estimated composite flexural strength. Only the tilt-up 3-2-3 panel TS2 and reinforced concrete PCI type panel with non-PS reinforcement and C-Grid® PCS3 were able to exceed their estimated composite strength. The other panels behaved partially composite.
- The results indicate that insulated sandwich wall panels provide adequate deformation capability to meet current blast response criteria. At a minimum, insulated PC CSW panels can be used in accordance with the current blast design limitations.
- The current blast response limits may potentially be increased to the proposed limits. These new limits provide information useful for improving the efficiency and economy of an already efficient and economic blast-resistant construction system. This cost-saving potential may also lead to more consideration for blast resistance being given to sandwich panels rather than other alternatives.
- The measured yield displacements are bounded by the composite and non-composite deflection predictions. In all cases, using the composite displacement predictions results in an underprediction of the actual displacement.
- The data generated as part of the research study can be used to develop response models and estimation methods using finite element analysis and simplified methods. This work is ongoing.
- The addition of unbonded reinforcement in the center of the panel did not increase the flexural deformation capacity of the panels. It is possible that this observation was due to poorly constructed unbonded regions.
- Observation of the damage to the multi-span systems revealed connection failures to the 3-2-3 panels. For these panels, the mid-height connections punched through the interior concrete wythe. The connection regions were not reinforced with any special detailing. Due to the negative moment demands at the region, the connection zone was subjected to


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multi-directional compression. In addition the flexure produced cracking. The combination of these demands and the lack of crossing reinforcement resulted in the punching failures observed. The 6-2-3 panels did not exhibit punching failures. The use of a solid zone at the connection region and the use of reinforcement crossing any potential punching zone would minimize this problem.

## 10.1. Further Research

This study examined the performance of conventional PC CSW construction. No special detailing was included to resist the effects of blast loading. Additional research is needed to examine the performance of these panels under axial demands. Furthermore, additional research should be conducted on the influence of enhanced blast specific design types.

Additional studies are being conducted using the results of this program to develop predictive models. The research is ongoing through a Cooperative Research and Development Agreement between the Portland Cement Association, the Precast/Prestressed Concrete Institute, the Tilt-up Concrete Association, the Air Force Research Laboratory, and faculty members from Auburn and Lehigh Universities.


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## LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

| | |
|---|---|
| ACI | American Concrete Institute |
| AFRL | Air Force Research Laboratory |
| $A_{ps}$ | area of prestressing steel in flexural tension zone |
| ASTM | American Society for Testing and Materials |
| ATFP | Anti-Terrorism and Force Protection |
| $b$ | width of compression face of member |
| COV | coefficient of variation (standard deviation divided by mean) |
| CRADA | Cooperative Research and Development Agreement |
| CSW | concrete sandwich wall |
| $d_p$ | distance from extreme compression fiber to centroid of prestressing steel |
| $E_c$ | elastic stiffness |
| EPS | expanded polystyrene |
| $f_{ci}$ | design compression strength at release |
| $f'_c$ | design compressive strength at 28 days |
| $f_{ps}$ | stress in prestressing steel at nominal flexural strength |
| $I_e$ | effective inertia |
| kip | thousand inch-pounds |
| $L$ | span length |
| LOP | level of protection |
| PC | precast |
| PCA | Portland Cement Association |
| PCI | Precast/Prestressed Concrete Institute |
| PDC | Protective Design Center |
| PIMA | polyisocyanurate |
| $P_{max}$ | maximum pressure |
| PS | prestressed |
| RC | reinforced concrete |
| TCA | Tilt-Up Concrete Association |
| WWR | welded wire reinforcement |
| $w_y$ | flexural strength |
| XPS or XEPS | extruded expanded polystyrene |
| $\Delta_{mid}$ | midspan displacement |
| $\Delta_{y\text{-}mid}$ | midspan yield displacement |
| $\Delta_y$ | yield deformation |
| $\theta$ | support rotation |
| $\theta$L | rotation at the onset of moderate damage |
| $\theta$M | rotation at the onset of heavy damage |
| $\theta$S | rotation at the onset of hazardous failure |
| $\theta$T | rotation at blowout |
| $\mu$ | ductility |
| $\omega_p$ | prestressed reinforcement index |


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