

# Deflection and Creep of Polyvinyl Chloride (PVC) Sheet Piling

by

Nathan Eric Touchstone

(Under the Direction of Sidney Thompson)

## ABSTRACT

Synthetic sheet pile has recently become a significant choice in design of sheet pile structures. While there is abundant literature concerning PVC as a compound there is little available concerning its use in a structural capacity. Design assistance is also limited and what exists is based on traditional steel sheet pile design which does not address issues seen in viscoelastic materials. Full-scale testing was completed using a series of PVC interlocking sheet piles. The sheet piles were subjected to loading for a duration of seven days while deflection and strain were measured. The deflection and strain were compared to theoretical values and previous laboratory testing. Existing deflection prediction equations for creep deflection tend to overstate deflection measured while the strain measured in full sheets is less than that of laboratory testing.

INDEX WORDS: Polyvinyl chloride, PVC, Sheet pile, Synthetic sheet pile, Creep, Sheet pile testing

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DEDICATION

To Karen Siegel Touchstone,  
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## 1.0 Introduction

Retaining walls are structures which provide lateral support where conditions disallow the soil to assume its natural slope. These retaining walls must support the lateral pressure created by the retained soil. There are many different types of retaining walls, gravity walls, semi-gravity walls, cantilever walls, counterfort walls and sheet pile walls.

Gravity walls, semi-gravity walls, cantilever walls and counterfort walls are all considered monolithic walls. These types of walls are constructed from concrete and rely on the weight of their material to resist the overturning and sliding forces created by the soil. Because of the size and material required, these structures are usually designed for holding heavy loads.

Sheet pile walls can be used for small and large waterfront structure or to retain soil. Sheet pile walls are normally designed as either cantilever sheet pile walls or anchored sheet pile walls. Both types of walls develop most of their resistance by being driven into the soil. The soil at the toe of the sheets, the passive side, resists the sheet being rotated forward by the soil behind the sheet, the active side. With a cantilever structure the penetration depth of the sheets determines the resistance of the sheeting. Anchored sheet pile walls have both the passive side soil resistance and a support or anchor that secures the upper portion of the sheet in place. Because the sheeting is only acting as a member to mobilize the resistance of the soil, materials of less weight and size are required to construct these structures. This also means that, in general, sheet pile structures will be smaller in height than gravity mass structures.

Sheet pile walls are normally constructed of wood, steel, aluminum, concrete or synthetic materials such as polyvinyl chloride and fiber-glass materials. In the past century, metallic

systems i.e. steel and aluminum were primarily used in the construction of sheet pile walls. However, Lampo et al. (1998) estimates that deterioration of marine structures (docks, walls, fendering systems) constructed from timber, steel and aluminum have cost the military and civilian marine communities approximately \$1 billion dollars annually. As with other infrastructure, sheet pile wall systems have begun to move to the use of synthetic wall materials to extend the lifespan.

The increased availability, low cost and increased lifespan of the synthetic sheet pile systems have led to their widespread use in both the government/municipal and private sectors. The first synthetic sheet pile was introduced over twenty years ago. Since its debut, Everlast Synthetic Products, one manufacturer of synthetic sheet pile, has amassed total sales of \$32.5 million with estimated industry wide sales of over \$120 million (DiScenza, 2010). Engineers at the US Army Corp of Engineers have found that the lighter weight sheet pile can save 30% to 50% of the cost on new installations over traditional steel, concrete or timber materials (Dutta and Vaidya, 2003). The low weight synthetic materials require no specialized equipment be used during installation, therefore allowing a decrease in the price per linear foot when installed in the residential market. This translates into a product that is more affordable for the average residential property owner.

With its increased use as a structural element, vinyl sheet pile has been at the forefront for both civil and structural engineers specializing in marine structures and shoring. During the early days of design and use, standard design methods common place to steel were used to design synthetic sheet pile wall systems. While the geometric properties of the synthetic wall materials are similar to steel sheet pile, the material properties are vastly different, not only in strength but also in stiffness and in impact. Steel sheet pile walls are designed primarily on

bending moments while synthetic sheet piles are designed primarily on wall deflection. Until the mid-90's both steel and synthetic wall systems used moment calculations as the primary design factor. However, this technique produced sizable wall deflections in the synthetic walls. While moments were well within the allowable moment limits, usually based on a factor of safety of two, deflections were well beyond acceptable limits. This has prompted engineers to refocus the basis for design of these type of wall systems on deflection.

The increased understanding of the limitations of synthetic sheet pile materials has allowed for a more comprehensive approach to design but there is still no unifying design standard to promote responsible design. The viscoelastic nature of PVC adds a new element in the design approach where considerations of short and long-term deflections are critically important. While metallic sheet pile will act in a predictable fashion based on traditional theory, synthetic materials have to contend with the effects of long-term creep and the possible consequences. However, current design philosophy with PVC sheet pile analyzes the wall structure based on a single modulus of elasticity (MOE) value thus ignoring any effects of creep. Van De Kuilen (1999) proposed that long-term deflection effects be taken into account using a creep deflection factor based on experimentally derived MOEs. The creep deflection factor is the ratio of  $MOE_{\text{design life}} / MOE_{\text{initial deflection}}$ . This technique results in a smaller design MOE. Because design is based upon deflection criteria this results in a larger required cross section. However, this technique has not gained favor within the industry because it might put the design at an economic disadvantage. No other technique has been suggested that takes into account the long-term field effects of 1) changing modulus based on load/stress, 2) aging effects and 3) the behavior of the PVC during cyclic loading.

This research is to begin the framework for a comprehensive design scheme for PVC sheet pile. To this end, the research is to achieve this by: 1) comparing the theoretical deflection of a simply supported beam composed of multiple vinyl sheet piles to data collected on a loaded frame of vinyl sheet piles, 2) comparing creep and strain data from laboratory testing on samples to data collected from the loaded frame tests and 3) calculating the apparent modulus of elasticity for sheets that have been stressed with varying loads for a time duration.

## 2.0 Literature Review

### 2.1 Existing Sheet Pile Design Guidance

Steel sheet pile design guides published by both US Steel (1984) and British Steel (1997) provide methodologies to design sheet pile bulkheads. These methodologies are based on the calculation of pressure diagrams, moments and shear forces. Traditional methods of calculation such as Free Earth, Fixed Earth and Rowe's Moment Reduction are highlighted. The Free Earth method assumes the lower end of the pile is driven only deep enough to restrain the wall but not induce large resisting moments at the tip of the sheet. The Fixed Earth method is driven deep enough into soil to act as a partially built-in beam subject to bending moments. Rowe's Moment Reduction Theory assumes that the bending moment in sheet piling decreases with increasing flexibility of the pile. All three design techniques assume that bending moment controls the design. In neither guide was there a direct limit or limit equation provided regarding deflection. In the US Steel manual displacement is discussed as a tool in the calculation of Rowe's Moment Reduction but not in direct comparison to a defined limit. The British Steel manual offers several examples of design calculations for bending moment and required section modulus of sheet pile but no example of deflection calculations were found. Because both manuals focus almost solely on moment based design they do not lend themselves well to the design of vinyl sheet pile walls.

The US Army Corp of Engineers (USACOE) Design of Sheet Pile Walls manual (EM 1110-2-2504) (1994) contains a section directly covering deflection but only in generic terms with no deflection criteria defined. The structural design section primarily focuses on the calculation and comparison of bending moments and shear. The manual does indicate that PVC



and other synthetics are possible design materials and lists multiple ASTM standards that apply to these type materials. These standards provide the methods of evaluating the structural strength of the various material options. The manual also contains a section on Special Design Considerations (Chapter 9) that covers design and/or installation issues inherent to general sheet pile wall systems and specifically to steel sheet pile. However, items unique only to synthetic sheet pile systems were not discussed.

The document “Interim Report – General Design Guide: PVC Sheet Pile” (Dutta et al., 2005), as published by the USACOE’s Cold Regions Research Laboratory, provides some specific design assistance for PVC sheet pile. While it recognizes that there are currently no national industry consensus standards on allowable stress or deflection in synthetic sheet pile it does promote the use of vinyl cell classification as a minimum design standard for the PVC material used in manufacturing the sheeting. The cell classification system (ASTM D4216-03) classifies materials using a eight digit code based upon the material’s composition and selected mechanical and material properties. The minimum property value determines the cell number. The classification system classifies PVC products according to the following characteristics: 1) base resin, 2) notched Izod, 3) drop dart test (procedure A), 4) drop dart test (procedure B), 5) tensile strength, 6) modulus of elasticity, 7) ductility and 8) coefficient of thermal expansion. This report recommends that PVC sheet pile used in design have a minimum modulus of elasticity of 377,000 psi. In the cell classification system this would correspond to a value of 3 in the sixth digit of the cell classification numbering scheme. In this manual, allowable deflection is held as a critical factor in design but the authors indicate that it is a serviceability limit rather than a true design criterion. A serviceability limit is interpreted to be a qualitative deflection limit based on appearance of the sheet pile after installation rather than an absolute predetermined

design value. They also state that, because of limitations in design software, deflections may be overstated and only a software package that can calculate deflections using more complex methods like Rowe's Moment Reduction should be used for deflection. They suggest that deflection from creep in PVC sheet piles can be ignored as a design criteria if the design stress for moment is kept below 3,200 psi. The report references EM 1110-2-2504 for general design criteria relating to sheet pile walls.

Three pieces of design related literature are available from Crane Materials International, a vinyl sheet pile manufacturer (Brown, 2006; Yeats, 2004, 2006). Crane Materials International (CMI) provides "white papers" on design. These papers describe techniques for design stress selection, deflection and choosing vinyl sheet piles using section modulus. Brown (2006) agrees with the use of cell classification system as a method of material property selection and that deflection from creep can be ignored if the design bending stress is kept below 3,200 psi. Brown proposed that a factor of safety of two be used on tensile stress and that 5% strain is also set as a limit for strain failure. Yeats (2004) agrees with the Dutta et al. (2005) that deflection is a serviceability limit and conventional methods over predict deflection. Traditional design methods normally used with steel sheet pile selection (i.e. use of moment calculation via an allowable stress and section modulus) are highlighted by Yeats (2006).

## 2.2 Available PVC Sheet Pile Parts Information

Based upon a review of design support literature provided by several manufacturers of synthetic sheet piles (CMI, Everlast Synthetic Products (ESP), Shoreline Plastics and Tidewall) all manufacturers provided technical data specifications on their product lines noting such properties as general dimensions, allowable moment, tensile strength, modulus of elasticity, section modulus and area moment of inertia. There is general agreement between manufacturers

that a nominal modulus of elasticity of 380,000 psi should be used in design. They also indicate that all published design values are nominal values and may vary. This information is generally found on their respective websites.

### 2.3 Polyvinyl Chloride (PVC) Material Behavior

PVC is a polymer composed of vinyl monomers with a chlorine atom covalently bonded to its carbon backbone. A series of these monomers form a “poly” chain. PVC sheet pile is formed by extruding PVC pellets/powder through a heated die. After extrusion the sheet pile is cooled to form the rigid sheet pile. As the temperature of the extruded material decreases the resulting solid is composed of both amorphous and crystalline structures. As with many polymers, PVC exhibits viscoelastic behavior. Creep is very common with these type of materials (Carter and Paul, 1991). The crystalline fraction of PVC is approximately 10%, a small but structurally significant fraction (Kim and Gilbert, 2004).

These crystal structures can be oriented by extrusion. Yarahmadi et al. (2003) determined that in extruded samples oriented by extrusion that elongation in the longitudinal direction was twice that of the elongation in the cross sample direction at failure. This effect was almost nullified when samples were heated to a temperature of 187°C leading to the conclusion these orthotropic effects are created by the extrusion process.

On the crystalline level loads placed on PVC are carried via two different steps. During the first step the amorphous polymer chains which connect the crystalline structures straightens until an initial equilibrium is reached. At this time, the initial bonds between the crystallites and poly strands in the amorphous areas are taut. During this step some of the smaller crystallites fail. Under increasing load, more crystallites rupture. The crystallite rupture produces an increase in creep action (Alfrey et al., 1948). Guo et al. (2005) noted these processes could occur

simultaneously and described them by the following processes: 1.) the time dependence of the bulk stress-strain relation, 2.) the time dependence of the fracture initiation and 3.) the kinetics of molecular flow and bond rupture on overstressed polymer chains. These processes are described graphically in Figure 1.

Many different studies have been conducted on creep in PVC. Alfrey et al. (1948) allowed PVC films to creep under load. The specimens were loaded, unloaded and then reloaded at differing time intervals. It was noted that the samples that were allowed to remain unloaded for the longest interval showed less deflection than samples reloaded immediately after being unloaded. Findley (1987) conducted creep testing on PVC specimens at 4,000 psi constant stress for a total of 230,000 hours (approximately 25 years). Using only the data from the first 1900 hrs. of testing the following equation was developed:

$$\varepsilon = \varepsilon^0 + \varepsilon^+ t^n \quad (1)$$

where  $\varepsilon$  is strain,  $t$  is time in hours.  $\varepsilon^0$ ,  $\varepsilon^+$  and  $n$  are constants developed based upon testing. This equation was shown to produce predicted creep values with good agreement to later data collected between 1,900 hrs. and 230,000 hrs. Van de Kuilen (1999) developed creep factors using C-Loc vinyl sheet piles. These creep factors were developed for various time intervals culminating in a 50 year creep factor ( $k_{\text{def}}$ ) of 2.3. Van de Kuilen proposed that bending deflection be predicted using the following equation:

$$u_{\text{fin}} = u_{\text{inst}}(1+k_{\text{def}}) \quad (2)$$

where  $u_{\text{fin}}$  is the final deflection,  $u_{\text{inst}}$  is the instantaneous deflection after loading and  $k_{\text{def}}$  is the corresponding creep factor.

Northstar, a manufacturer of PVC sheet piling, had creep tests performed by an independent laboratory on samples taken from mono-extruded PVC sheet pile. This testing was

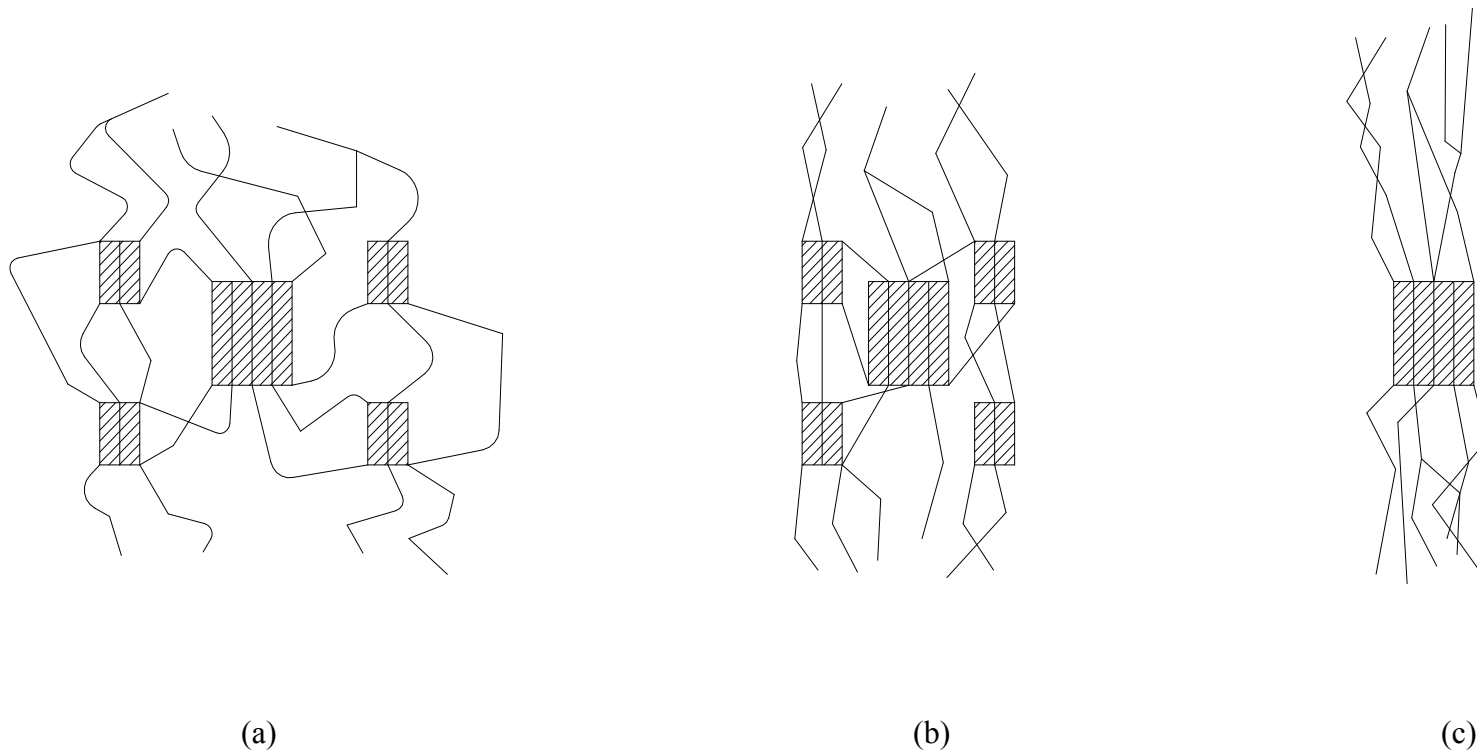


Figure 1. PVC Macromolecular Structure: (a) at rest, (b) under a load engaging the amorphous poly chains and (c) after rupture of smaller crystalline structures. (Alfrey et al. 1948)

performed on 0.40" thick material samples under creep loads of 2,667 psi and 4,000 psi for a duration of 10,000 hrs (SGIa, 2007). They determined total strain at one, 10, 100 and 10,000 hrs and associated creep rate. Everlast Synthetic Products, another PVC sheet pile manufacturer, performed similar creep testing with a co-extruded PVC sheet pile product of 0.25" thickness. The duration of loading and stress levels were the same with one exception of an additional test specimen creep loaded at 5,000 psi (SGIb, 2007). A summary of these test are shown in Table 1. The Northstar product showed an increased total stain over the Everlast product through all time periods. A possible explanation for these differences is that the Northstar product is manufactured using a mono-extrusion process with recycled vinyl while the Everlast product is manufactured using co-extrusion process. The observed differences were presumed to be caused by differences in formulation.

Most vinyl sheet piles have some post-industrial, pre-consumer recycled PVC in its core substrate. Yarahmadi et al. (2001) tested mechanical properties of unplasticised PVC material that had previously underwent five extrusions. While the tensile properties of these materials remained the same over the five extrusions the overall predicted life-expectancy of the samples decreased to only 47 years after the fifth extrusion, a decrease of approximately 100 years from that of samples from the first extrusion. Arnold et al. (1996) studied the use of recycled PVC bottles and the effects produced by introducing recycled materials into the manufacturing processing i.e use of virgin material versus recycled flake versus recycled powder. Samples produced using 100% recycled flakes were shown to have significantly lower tensile properties because of impurities that were introduced by the flake. Samples produced using 100% recycled powder showed better tensile strength than the flake but slightly lower fatigue resistance than the virgin material. This would be applicable to PVC sheet pile because the majority of core

Table 1 - Total Strain Data from Bench Testing on Various PVC Samples at 4,000 psi Stress					
	Time Data Measured				
Source	1 Hr.	10 Hr.	100 Hr.	1000 Hr.	10,000 Hr.
Everlast Vinyl Sheet (SGI, 2007a)	1.48	1.64	1.89	2.23	2.78
Northstar Vinyl Sheet (SGI, 2007b)	1.56	1.77	2.12	2.77	3.45

substrate PVC used in the extrusion of PVC sheet piling comes from recycled material from internal sources (from reground materials within the same manufacturing plant) and external sources (from reground materials secured from other vendors such as PVC fencing, PVC window lentils, PVC siding).

#### 2.4 Full-Scale Synthetic Sheet Pile Testing

Vaidya et al. (2005) conducted four-point bend tests on two interlocked “Z” configuration vinyl sheet piles. Three sets of sheets were loaded to a limit of 1,327 lbs. over a span of six feet. An average deflection of 0.12” was observed. A finite element model was constructed mimicking the test setup and executed. The resulting calculated deflection was 0.15”.

Full-scale testing of fiber-reinforced polymer (FRP) sheet pile has been conducted. Durability, flexural and shear rigidity and deflection creep have all been analyzed based on full-scale testing of paired “Z” configuration sheets (Shao and Kouadio, 2002, Giroux and Shao, 2003, and Shao and Shanmugam, 2004). Shao and Shanmugam (2004) found that the creep model determined by Findley (1987) agreed well with sheet data collected after one year of loading. Fiber-reinforced polymers are different from the PVC sheet pile because of these polymers are thermoset polymers. Unlike PVC, a thermoplastic polymer, FRP cannot be reground and recycled for use in another processing. The glass matrix reinforcing the FRP sheeting provides significantly greater strength than does the PVC.

#### 2.5 Summary

The review of available literature shows that, from a design perspective, many of the same techniques used for classical steel sheet pile design have been retained for synthetic sheet pile design. The use of these designs have been adapted for the smaller moments and loads that



the synthetics are capable of carrying. However, this industry still lacks a consensus industry standard design methodology and there is not a general agreement on addressing specific design issues using polymers. Even though deflection is recognized as a critical design issue in the use of polymer sheet piles, it is still seen as a secondary concern to allowable moment for design.

PVC as a general material is a well understood material with significant data driven models available for comparison to future vinyl testing. However, limited full-scale testing data of structural PVC members is available. Full-scale testing of FRP sheet pile is more readily available and includes data on durability and rigidity of these members. However, in the author's opinion this data is not applicable to vinyl sheeting.

### 3.0 Objectives

The objective of this study is to evaluate the behavior of vinyl sheet pile in a full-scale application of loading with particular attention on the deflection and creep behavior of the sheeting as compared to theoretical and previous bench-scale experimental results. To achieve this end the following items must be addressed:

- 1.) Determine the deflection of typical vinyl sheet piling under an initial uniform load and after a period of time of seven days.
- 2.) Determine the total strain after 100 hours of loading in vinyl sheet piling at discrete points and compare these experimental values to existing data.
- 3.) Apply this information to further the needs for a general industry standard design methodology.

## 4.0 Materials and Methods

### 4.1 Multiple Sheet Frame Design

Two wooden frames were constructed to allow placement of five sheets of interlocked PVC sheet pile to be loaded. Figures 2 through 7 show the general construction of both frames from a side and end perspective and constructed frame photos. The two frames share a common overall structure with a variation in support members. Each frame consisted of two end and side assemblies. The first frame, hereby referred to as Frame 1, was constructed using No.2 Southern Yellow Pine 6x6 nominal timbers. Each end assembly consisted of a lower and upper assembly. During loading the PVC sheet pile was sandwiched in-between and secured by these two assemblies. The upper assembly acted to hold the sheeting in place once mechanically connected to the lower assembly. The lower assembly was constructed with four 30" tall legs, made from double 6x6 timbers, spaced at 30" on center. The two end assemblies were connected by two side assemblies which consisted of 6x6 timbers with three 30" support legs at 60" on center. The purpose of the side assemblies was to stabilize the two end assemblies. Sheets were placed in the frame and free spanned from one end assembly to the other. The upper end assembly consisted of a 6x6 timber at 10' length. Five 5/8" dia. all-threads were used to secure the upper end assembly to the lower end assembly, thereby sandwiching the sheet pile in-between. Loading of the frame was executed by constructing a 7'-6"x11'x4' box from 3/4" thick plywood. The end walls of the box were attached to the top members of the end assemblies for support. The end walls were also cut to fit the corrugations of the sheet pile to allow for a tighter fit. The side walls of the box were reinforced with rows of 2x6 boards.

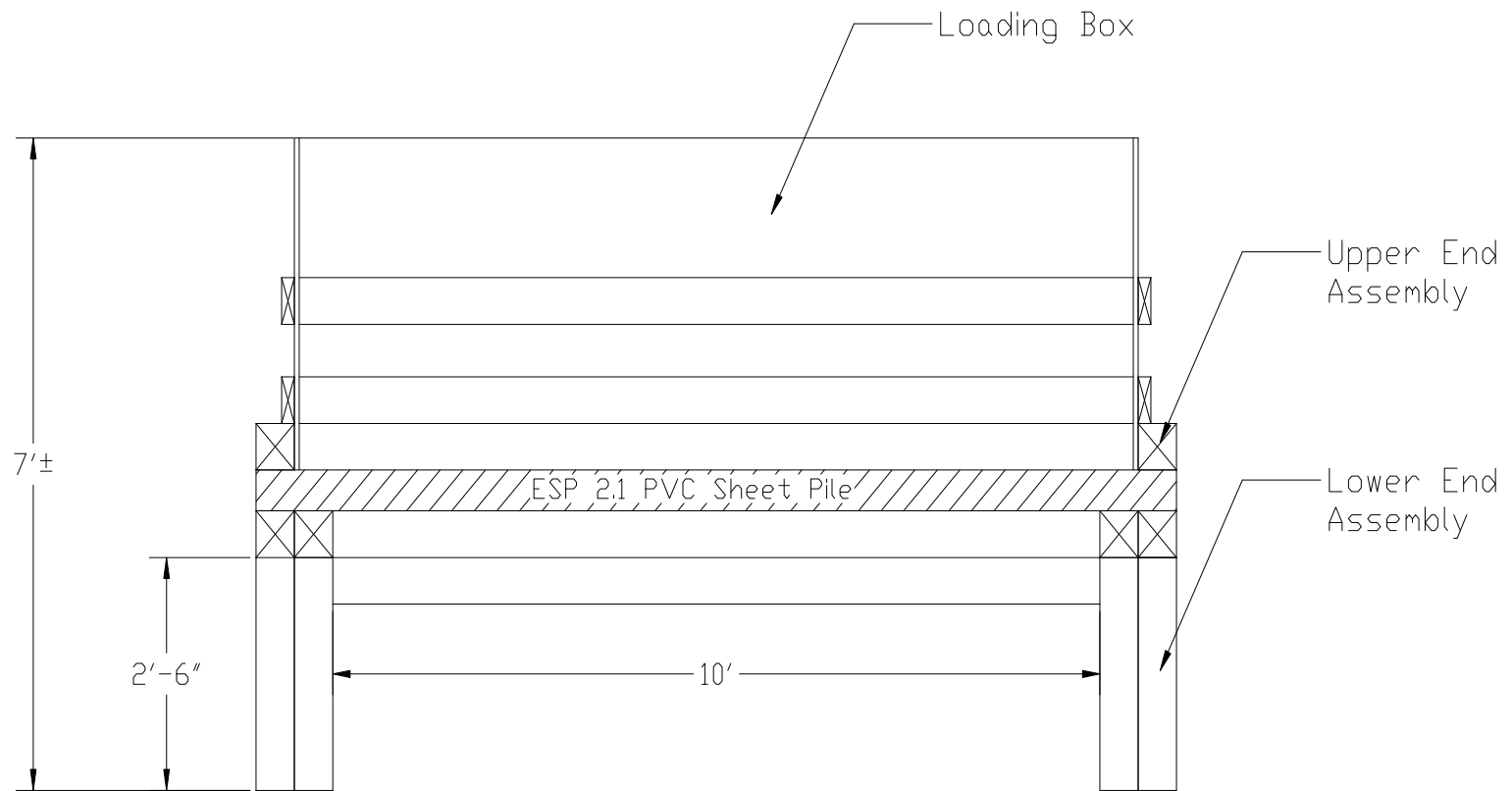


Figure 2. Multi Sheet Testing Frame (Frame 1) – Side Diagram

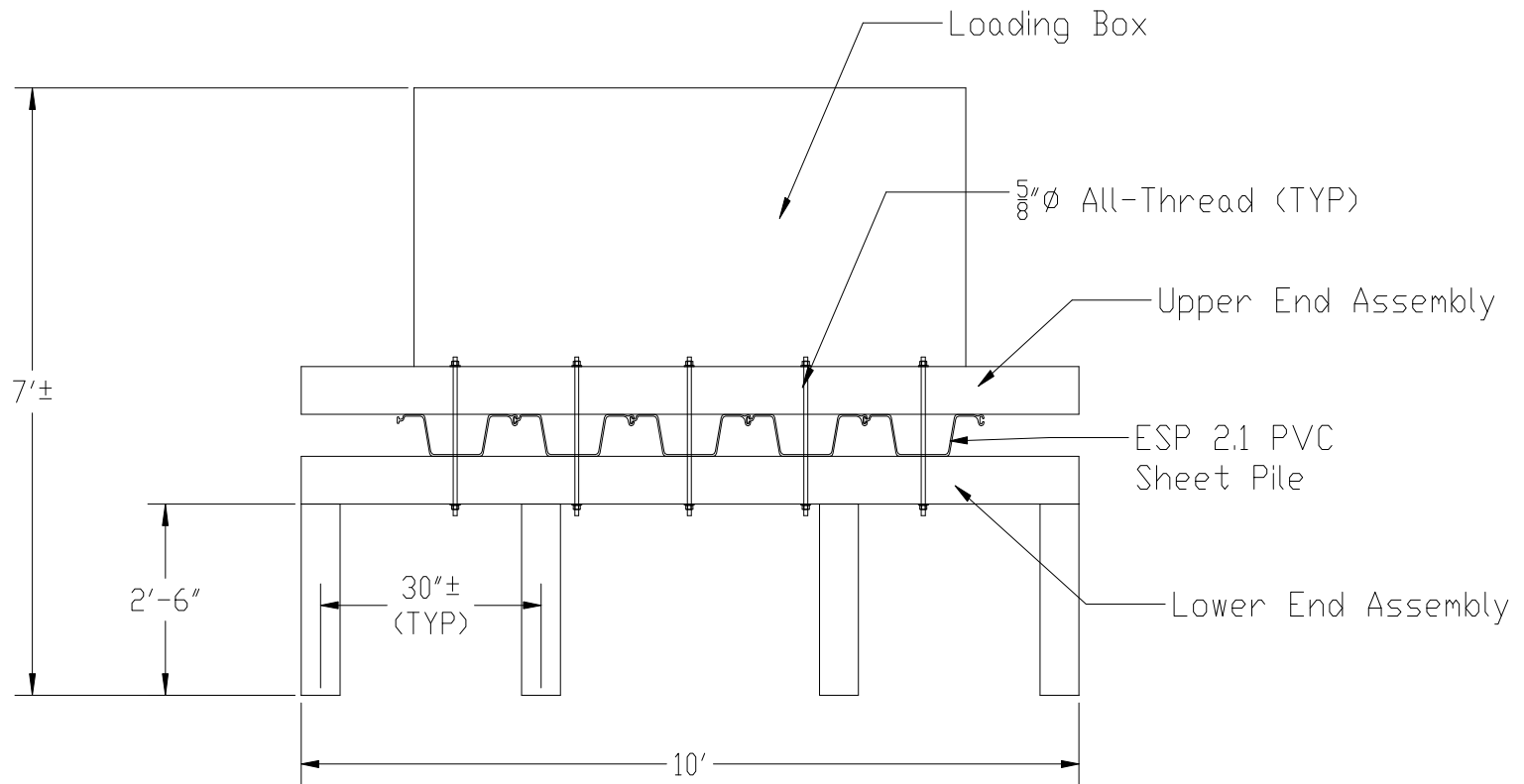


Figure 3. Multi Sheet Testing Frame (Frame 1) – Cross Section Diagram



(a)

(b)

Figure 4. Constructed Frame 1 Photos: (a) Side View and (b) Cross Section View

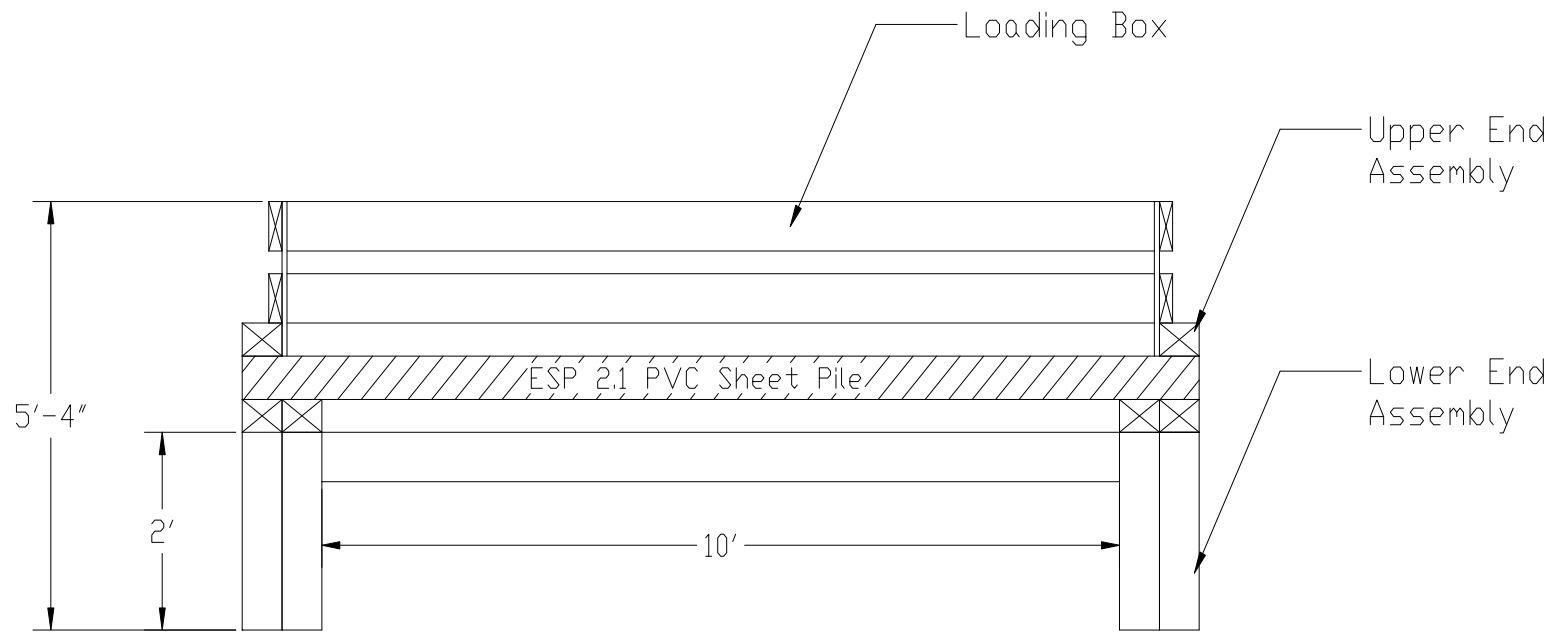


Figure 5. Multi Sheet Testing Frame (Frame 2) – Side Diagram

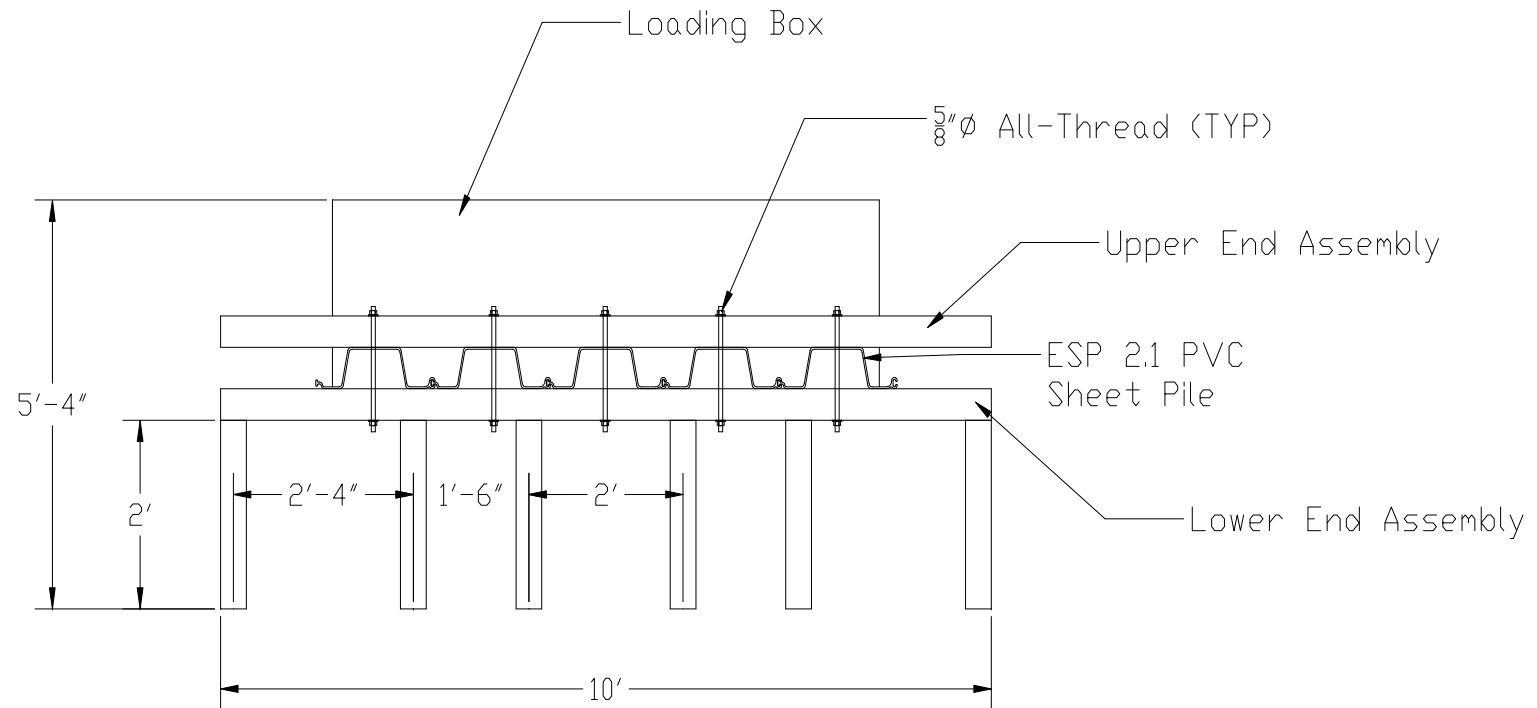


Figure 6. Multi Sheet Testing Frame (Frame 2) – Cross Section Diagram





(a)

(b)

Figure 7. Constructed Frame 2 Photos: (a) Side View and (b) Cross Section View

The second frame, hereby referred to as Frame 2, was constructed in a similar fashion to the first frame. For this frame 4x6 nominal timbers were used as the major members. Additional leg supports were incorporated into the second frame to account for material reduction from the design of the first frame. The loading box was constructed in a similar manner. However, the height was only 24". Both frames clamped the ends of the sheets in a like manner.

Both frames were designed and constructed to hold five sheets to provide an analogous system to sheet pile installed in the field. Each sheet is connected to the neighboring sheet through an interlocking system, which acts to brace the neighboring sheet when it experiences forces trying to move it out of plane. In this test configuration the outer sheets were considered sacrificial with data collection performed only on the center sheet.

#### 4.2 Single Sheet Frame Design

A single sheet test frame was constructed in a similar manner to that of the multiple sheet frames. End assemblies were constructed from an upper and lower assembly. The two end assemblies were connected together by a 2x6 board on each side to act as support. All sections of the end assemblies were constructed by laminating three sections of No. 2 Southern Yellow Pine 2x6 timbers together. Each end assembly was designed with a base contact area of 30" width and legs at 24" height. Two 1/2" dia. all-threads were used to secure the upper end assembly to the lower end assemblies. The loading box had the outside dimensions of 17"x48"x84" and constructed from the same plywood as the multi sheet frames. Two rows of 2x6s were applied to the outside of the box to act as supports. Five 5/8" dia. all-threads were used as through bolts for each row of 2x6s. Out-of-plane deformation was prevented by using two 2x6s as railing along the interlocks of the sheets. Figures 8 and 9 are end and side diagrams of the single sheet frame and Figure 10 is constructed frame photos.

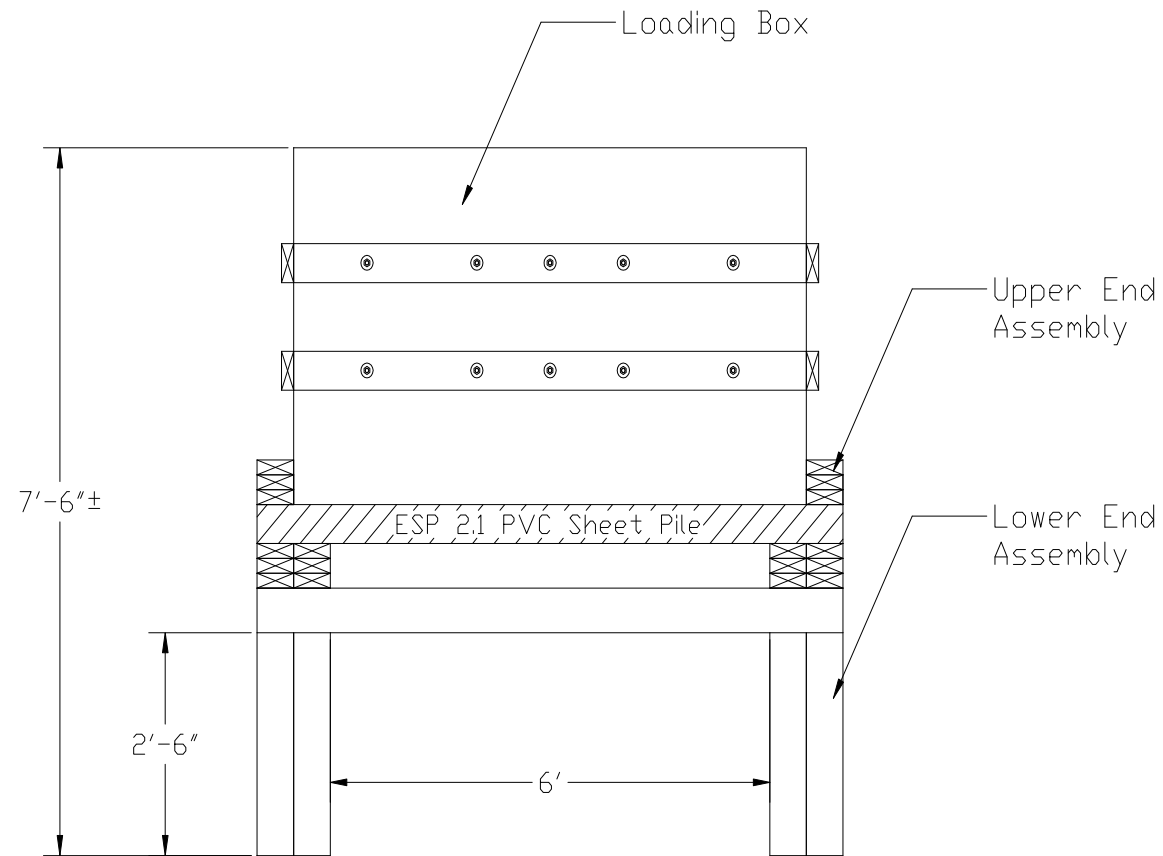


Figure 8. Single Sheet Testing Frame – Side Diagram

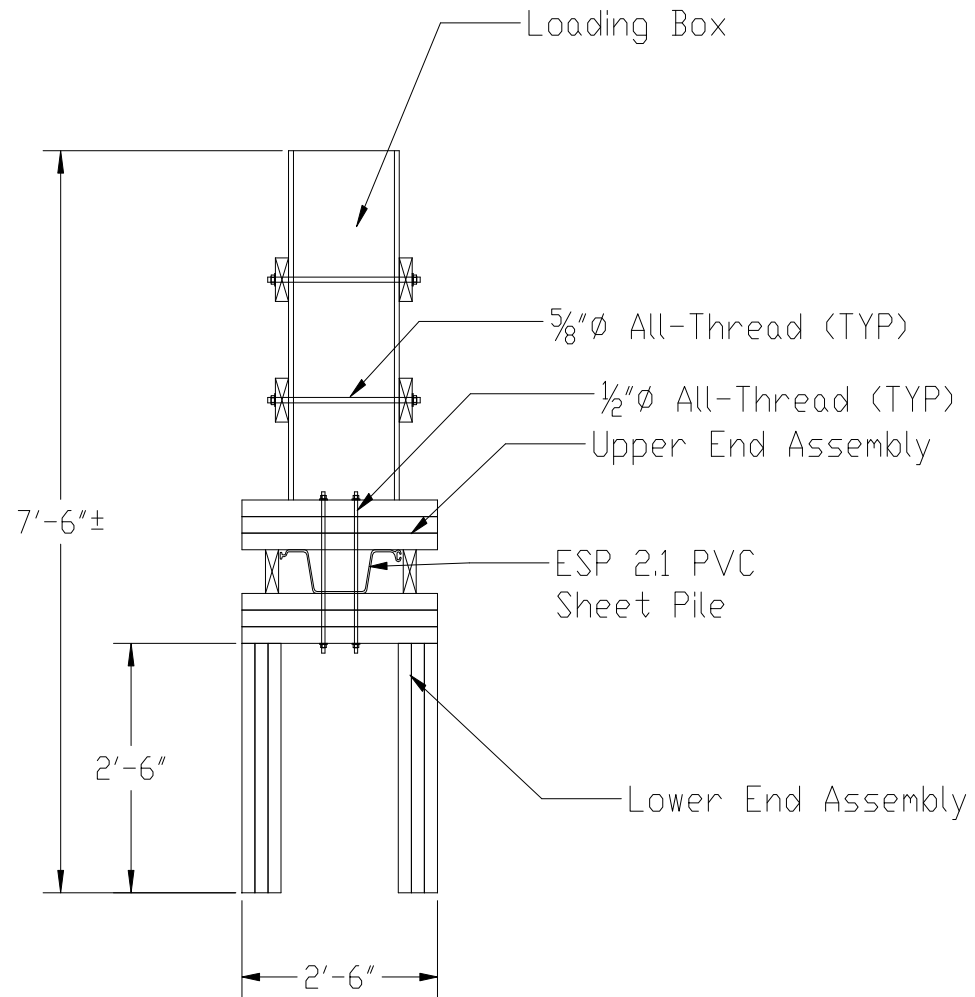


Figure 9. Single Sheet Testing Frame – Cross Section Diagram

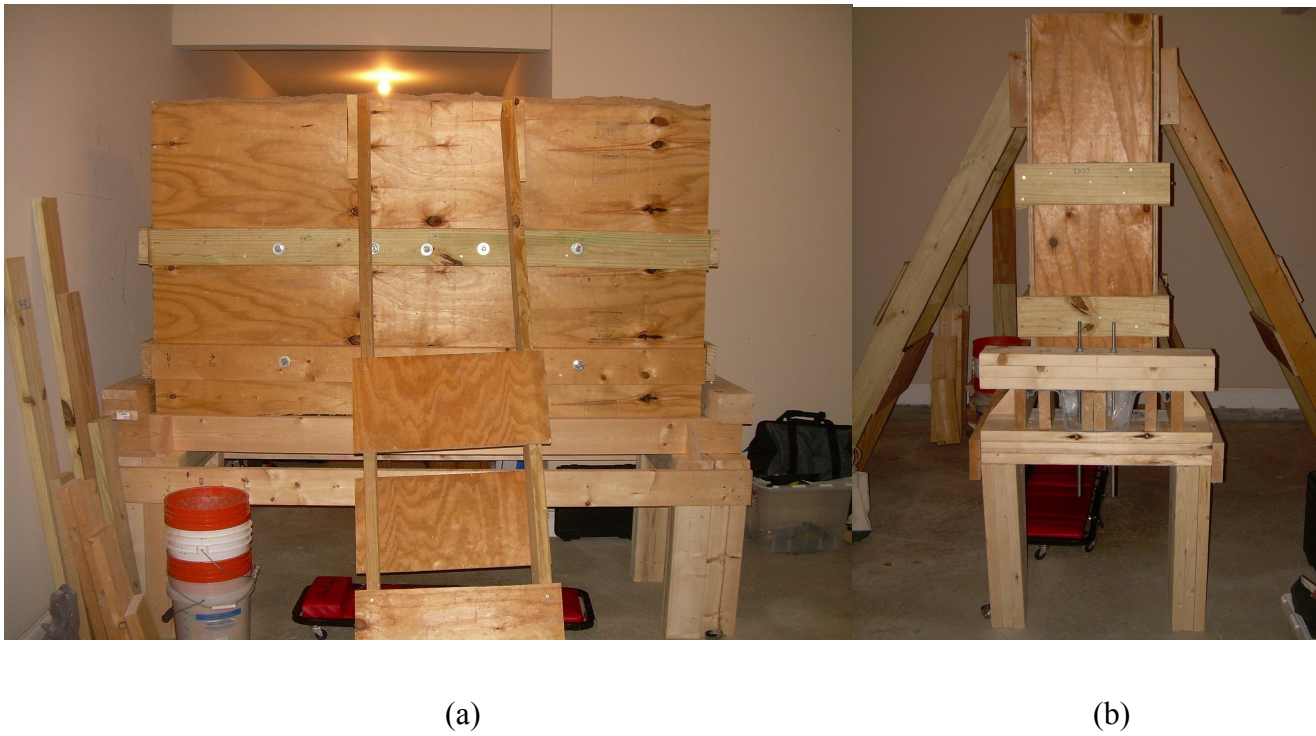


Figure 10. Constructed Single Sheet Frame Photos: (a) Side View and (b) Cross Section View

### 4.3 PVC Sheet Pile Selection

The PVC sheet pile selected was the ESP 2.1 as produced by Everlast Synthetic Products, LLC in Woodstock, GA. The ESP 2.1 published values for geometric and material properties are:

Depth of Section = 5.25"

Width of Section = 18"

Thickness = 0.23"

Moment of Inertia (I) = 20.3 in<sup>4</sup>/ft

Section Modulus (Z) = 7.7 in<sup>3</sup>/ft

Ultimate Tensile Stress = 6,300 psi

Modulus of Elasticity (E) = 380,000 psi

Figure 11 shows the cross section of the ESP 2.1 part. This is the smallest box cross section profile manufactured by Everlast Synthetic Products. The sheet is a co-extruded sheet pile that uses titanium dioxide as its main UV degradation inhibitor. This sheet was selected because a significant deflection and stress can be achieved with a small uniform loading. Since the interlocks are located on the same flange side, the sheets geometry allowed for the testing of two different configurations: interlocks in compression and interlocks in tension. Twelve feet long sheets of ESP 2.1 sheet pile were used in the multiple sheet testing and eight feet long sheets of ESP 2.1 sheet pile were used in the single sheet testing.

The extrusion process, especially with parts of increased thickness, is known to have the produced parts which deviate from nominal by a tolerance range of  $\pm 8\%$ . To account for these variations, five random samples of the ESP 2.1 part were selected and measured for thickness.

The collected data was used to modify a CAD profile of the 2.1 part, Figure 12. Based upon this

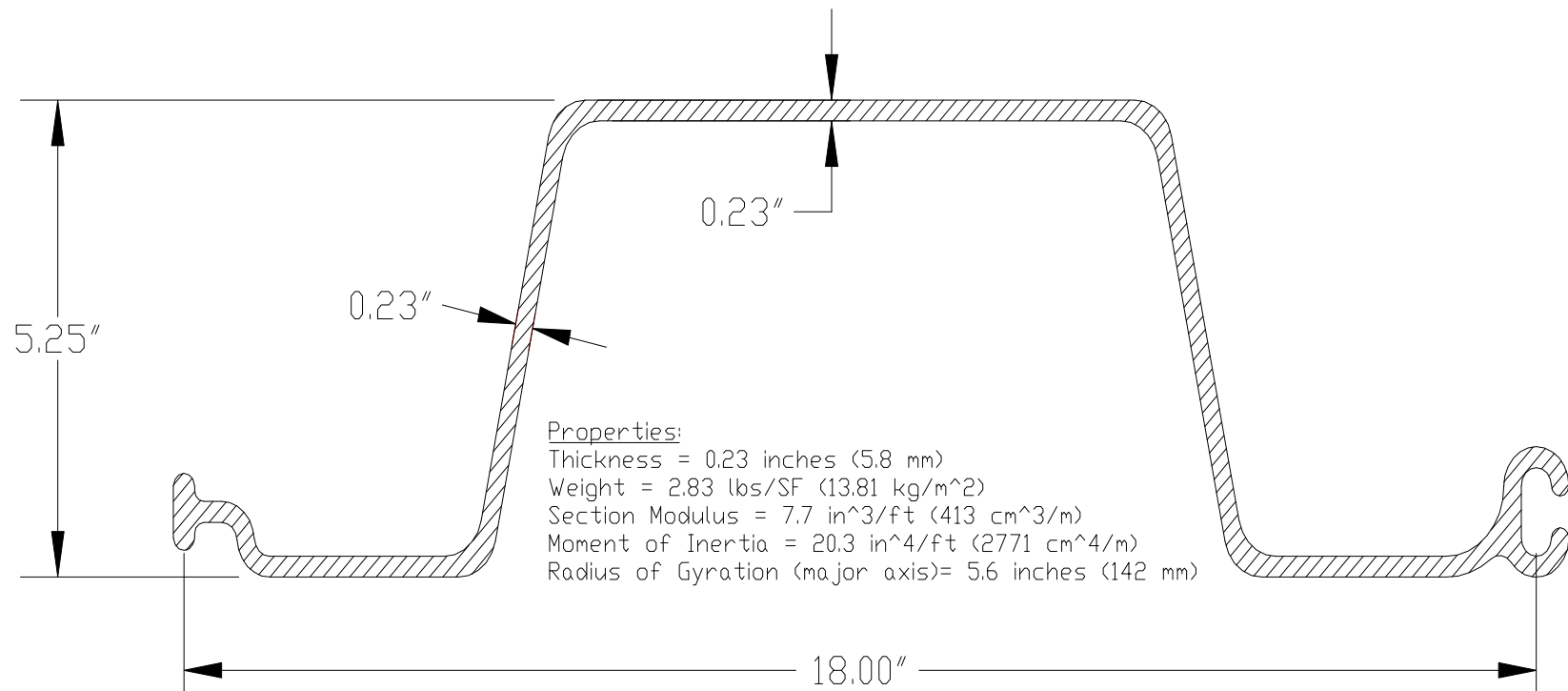


Figure 11. Everlast ESP 2.1 Vinyl Sheet Pile Part Drawing

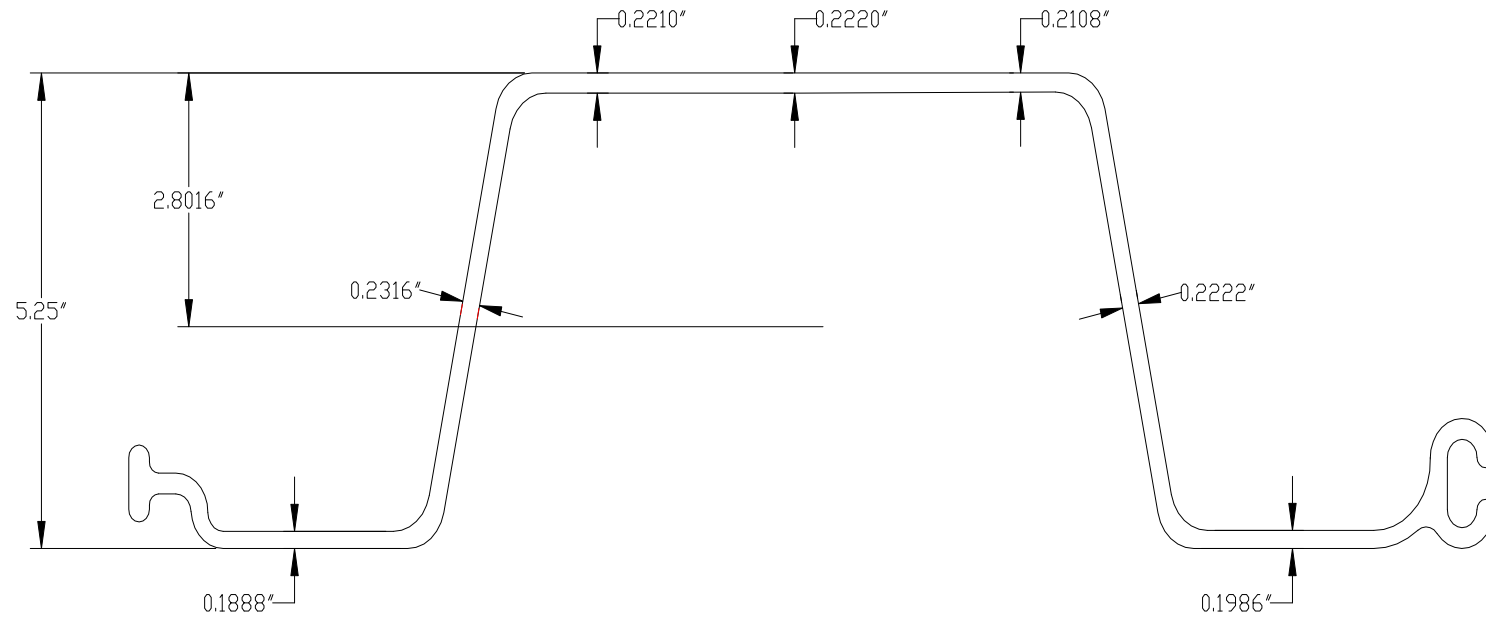


Figure 12. Everlast ESP 2.1 Vinyl Sheet Pile Modified Part Drawing Based on Measurements from Five Different Samples



CAD drawing, a new moment of inertia of  $18.85 \text{ in}^4/\text{ft}$  and section modulus of  $7.18 \text{ in}^3/\text{ft}$  were calculated and used in all following calculations unless specifically noted.

The sheets used for the 18" and 24" loading tests were produced on July 25, 2010 and June 13, 2009, respectively. Theoretically there should be no differences between the sheets manufactured at different times because of quality control procedures.

#### 4.4 Experiment Execution

Three series of tests were performed using the two multi sheet frames. Tests were conducted at the Bioconversion Research and Education Center, The University of Georgia, Athens, GA. These tests were separated into overall uniform load and orientation of the interlock of the sheet pile. Each series of tests consisted of four load on/load off tests. Frame 1 was used for two series of interlock-in-compression (IIC) tests and Frame 2 was used for one series of interlock-in-tension (IIT) tests. Loose sand was chosen for the loading medium because of its ability to conform to the corrugations and it provided a density greater than water. Both Frame 1 and 2 were loaded with sand for seven days in six inch layers up to a depth of 18". The sand was loaded and leveled, by hand, to corresponding grade marks. The grade marks were located at six inch increments on the side of the plywood box. For the 18" IIC and IIT tests, deflection measurements were made along the sheet immediately after loading ended, then again after seven days of loading and directly after unloading. Frame 1 was used for a second series of tests involving the sheeting oriented in a compression configuration and loaded with 24" of sand. For all three tests the sand was allowed to remain in the loading box for a period of seven days and then be removed. For the 24" IIC tests, deflection data was collected following each loading, at 100 hrs. load duration, at seven days load duration and directly after unloading at seven days. Tests were conducted between May and October. Both test frames were located outside under a

covered structure. All tests were conducted under warm weather conditions (ambient temperature > 50°F). Testing was terminated during the third week of October because of decreasing temperatures and their possible effects on the sheets' stiffness. During cold temperatures PVC loses ductility thereby increasing its brittleness and modulus of elasticity.

It is important to note that the 18" and 24" marks did not designate that the soil depth was uniform across the panels but was only a grade line to measure against during loading. Based on the deformation of sheet during loading the actual equivalent load on the sheet pile was a combined uniform and triangular load (see Figure 13). This increase in load was caused by the deflections of the sheets during loading of the box.

Sheet deflection was measured at five locations on sheets in Frame 1 (see Figure 14). These locations were the center point of the center sheet and 11.8" and 23.6" to each side of the center point along the center sheet's longitudinal axis. The deflection from Frame 2 was taken at two lines flanking the central line of the sheet pile on the outer flanges (see Figure 15). Deflections were measured at the same distance from the center point of the sheets for both the IIC and IIT tests. Deflections were measured using a Bosch DLR 130 Distance Measurer laser with an accuracy of  $\pm 1/16$  in. Strain measurements were taken using a Meda Series 725 6" electronic caliper. All deflection data was collected as the distance from grade below sheet to a point on the sheet face. The net distance from the initial distance reading to the next was taken as the amount of deflection.

Sand was loaded into the plywood box with little to no active compaction. The compacted bulk density of the sand was determined by placing a steel Winchester bushel known volume container (AACC Method 55-10.01) at mid-depth of the sand. For tests using 18" of sand, the container was placed at a depth of approximately nine inches within the sand. When

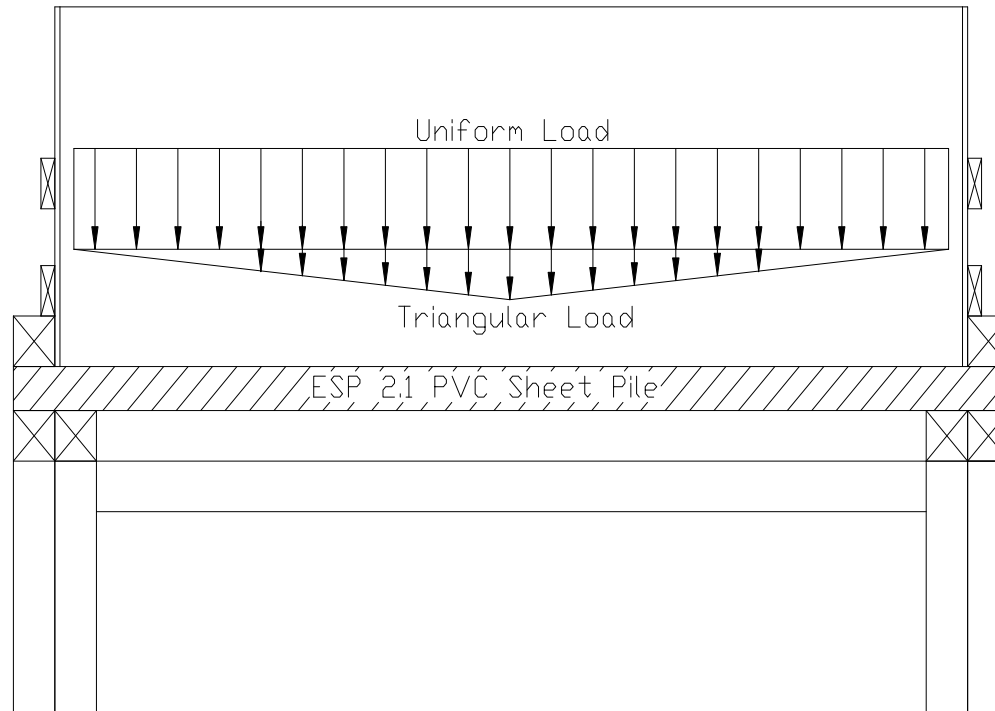
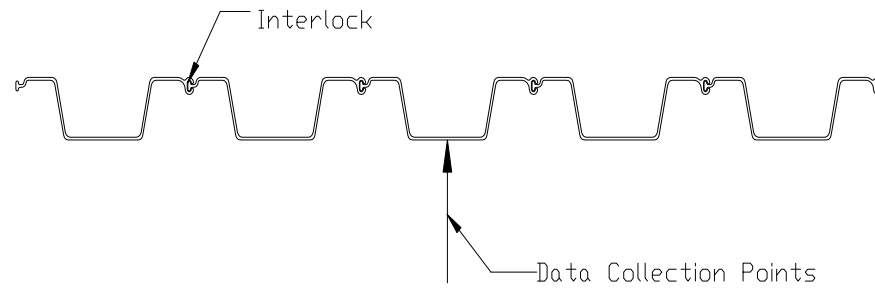
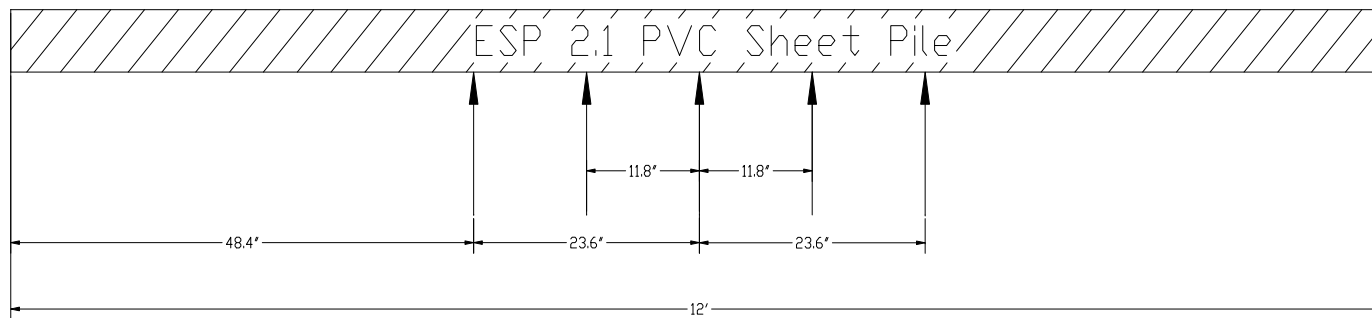


Figure 13. Multi Sheet Frame Loading Diagram

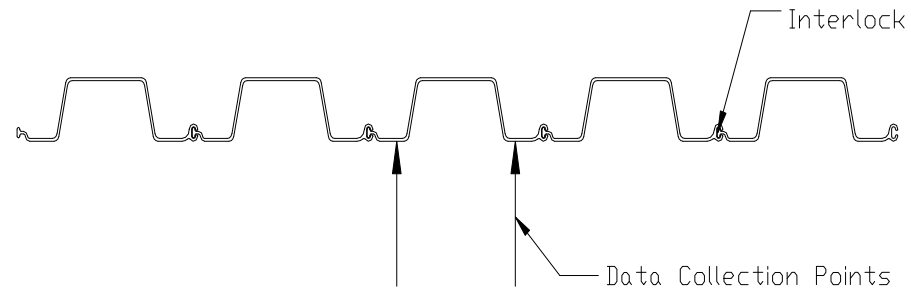


(a)

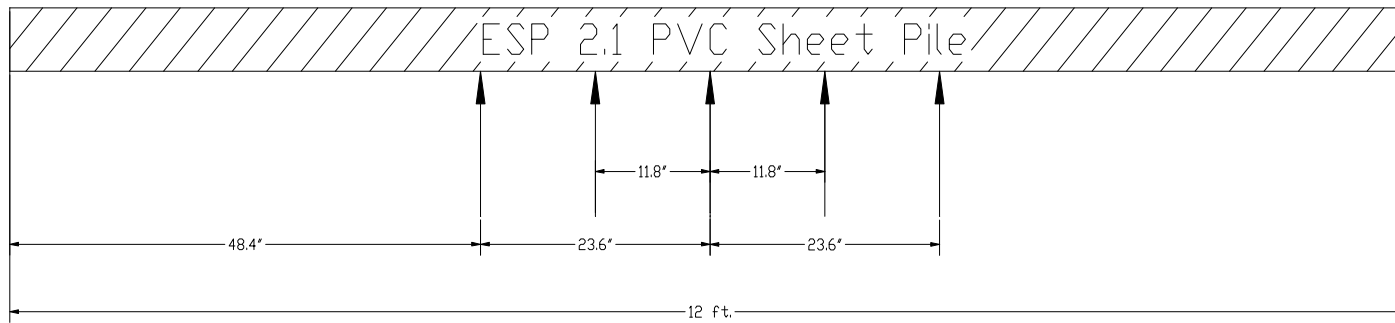


(b)

Figure 14. Multi Sheet Frame (Frame 1) – Five Sheets of ESP 2.1 Sheet Pile – Interlock-in-Compression – Data Measurement Points: (a) Cross Section and (b) Side View



(a)



(b)

Figure 15. Multi Sheet Frame (Frame 2) – Five Sheets of ESP 2.1 Sheet Pile – Interlock-in-Tension – Data Measurement Points: (a) Cross Section and (b) Side View

using 24" of sand, the container was placed as a depth of approximately 12" within the sand. The Winchester bushel container has a known volume is 2150 in<sup>3</sup>. The tare weight of the container was 3.3 lbs. The average compacted bulk density of the sand was determined using this procedure to be approximately 90 pcf.

In addition to deflection data, strain data was collected on the vinyl sheets when loaded with 24" of sand for IIC tests. Strains were taken at the centerline of the sheet over gage lengths of 10", 20" and 30" lengths. Strain data was collected immediately after loading, at 100 hrs. after loading and at seven days after loading.

A single sheet test was performed at the residence of the author in Marietta, GA. For this test a frame was constructed which held only one sheet. The frame was eight feet long and 2.5' feet wide. A plywood box was once again used to contain sand during loading. The plywood box containing the sand was 7' long by 15 inches wide and 4' tall. The PVC ESP 2.1 sheet pile (eight feet long and 18" wide) manufactured by Everlast Synthetic Products was again used in these tests. The sheets were oriented in the frame in a compressive loading configuration (IIC). The loading box was loaded with a total known weight of 3,780 lb. Based on the dimensions of the frame and sheet this produced a uniform load of approximately 540 lb/ft on the sheet pile and a stress of 2667 psi within the sheet. This is the same stress level that Northstar and Everlast tested "dog-bone" samples of PVC sheet pile in the laboratory and determined total strain values.

Deflection and strain data in the single sheet test was collected using a similar procedure by measuring the distance from the grade level to the deflected sheet pile. For these tests a greater density of data points was collected across the face of the sheet. Data was collected at the locations shown in Figure 16. Five deflection values were collected at each six inch interval from the center to a distance of 18". This resulted in a total of 35 data points collected per collection

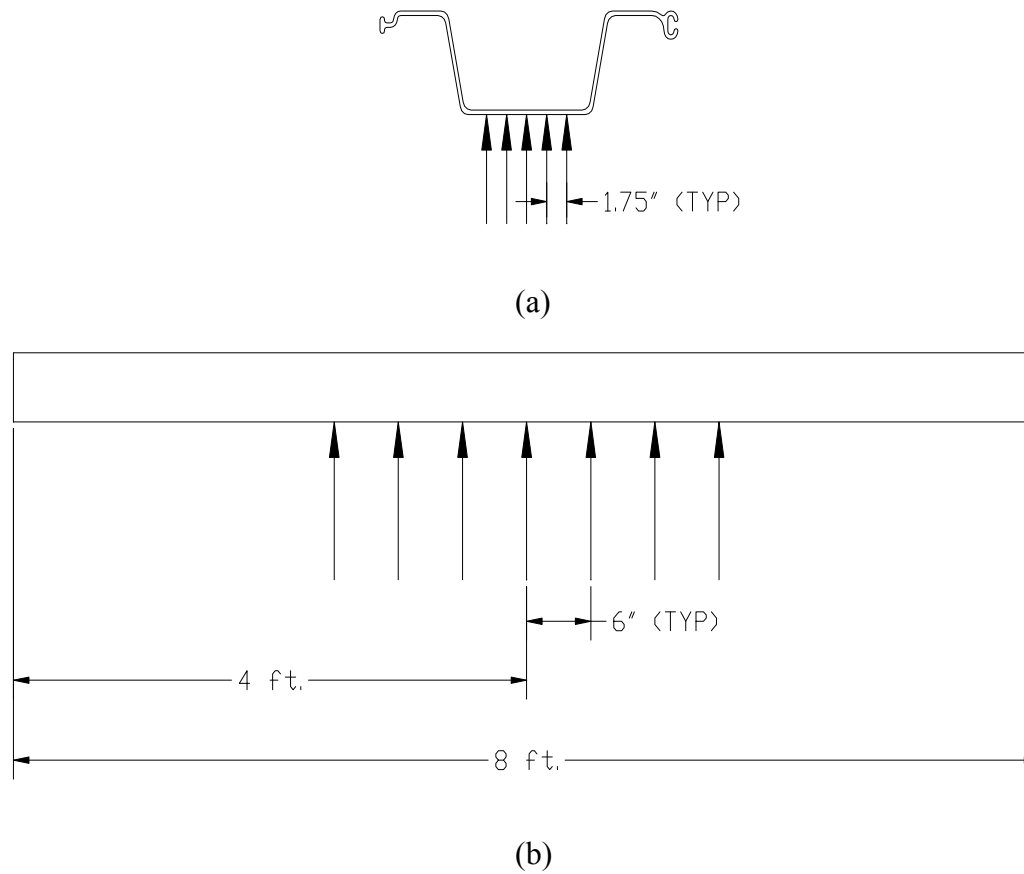


Figure 16. Single Sheet Frame – Interlock-in-Compression – Data Measurement Points: (a) Cross Section and (b) Side View

episode. The strain data was taken in groups of three at the center, six inches from center in both directions and at 12" from center. The strain data was taken over a length determined by two indentation points at each collection point, over a gauge length of approximately one inch.



## 5.0 Results and Discussion

### 5.1 Deflection of Multi Sheet Pile Testing

Deflection data from initial loadings were plotted in Figures 17 to 19. It was noted that with each successive test the deflection increased significantly from the previous test. This effect was seen in both Frame 1 tests and the Frame 2 test. Incremental deflection samples from a single series of tests (18" sand) are shown in Figures 20 and 21. The general trend described by the former figures can also be seen in these individual plots. For each test there was an increase in deflection over the face of the sheet. This indicates that there is a decline in stiffness of the sheet after each test. Bending stiffness is the product of modulus of elasticity and moment of inertia of the bending member. Based upon visual inspection, the general cross sectional properties of the sheeting appeared to be uncompromised. This would indicate that the decreased stiffness is a result of a change in the modulus of elasticity of the material with iterative loading. It is important to note that the sheets returned to within 1/8" of the pre-loading deflection once the sand was removed and the sheet was allowed to recover over a seven day period. These patterns of increasing deflection appear to correspond to those predicted by Alfrey et al. (1948). It is presumed that after the first loading case the sheets experience some engaging of the amorphous polymer chains of the PVC substrate as described by Alfrey et al. which led to the initial deflection. Over time it is thought that the continuous loading engages the crystalline structures. The smaller structures would rupture under stress and allow creep deformation to occur. Once the load is removed the amorphous structure acts to restore the original conformation of the sheet. The reloading of the sheets (Test J+1) within a relatively short time

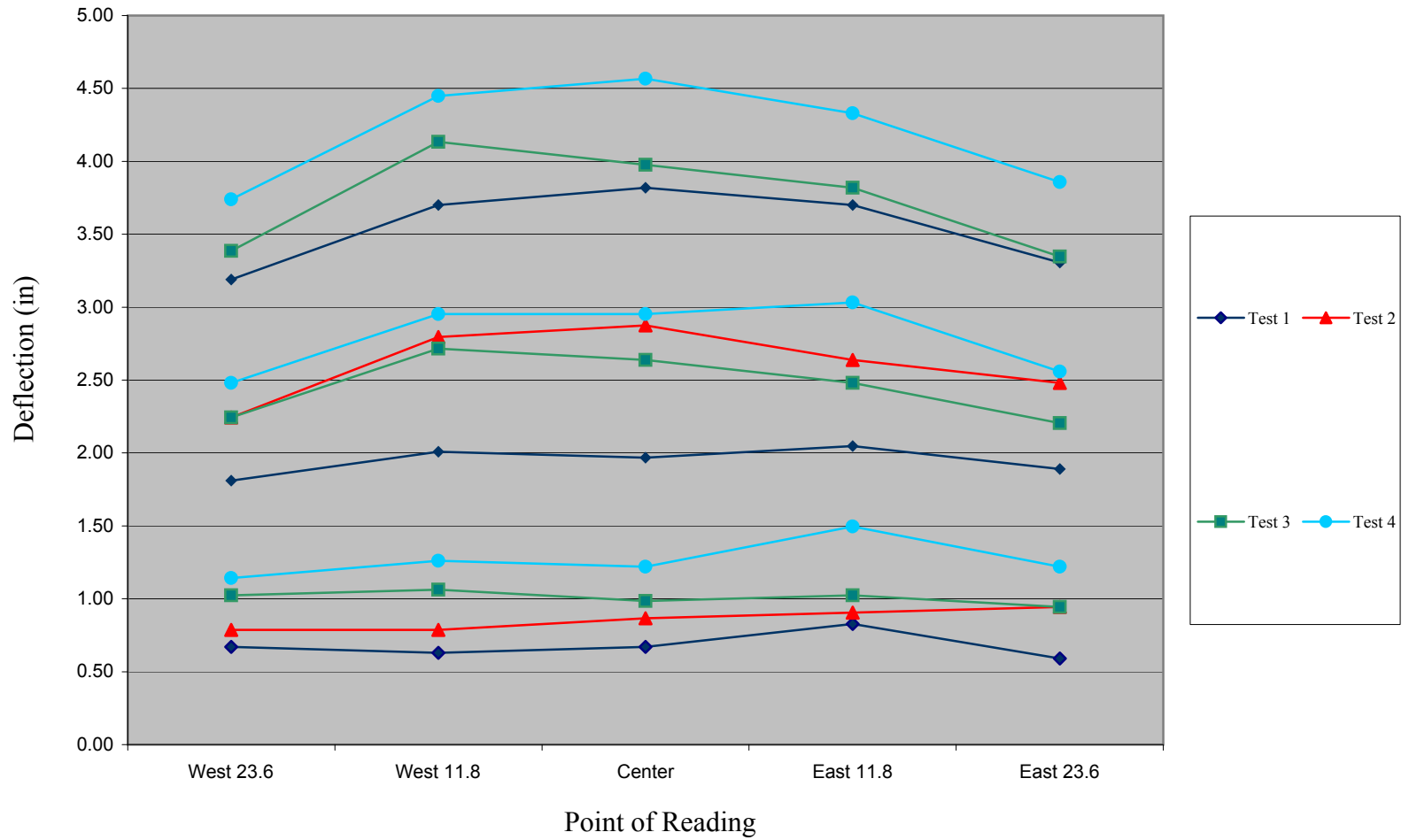


Figure 17. Incremental Deflection for All Four Multi Sheet Test Series of Vinyl Sheet Pile with Interlock Placed in Compression - 18" Loading Maximum

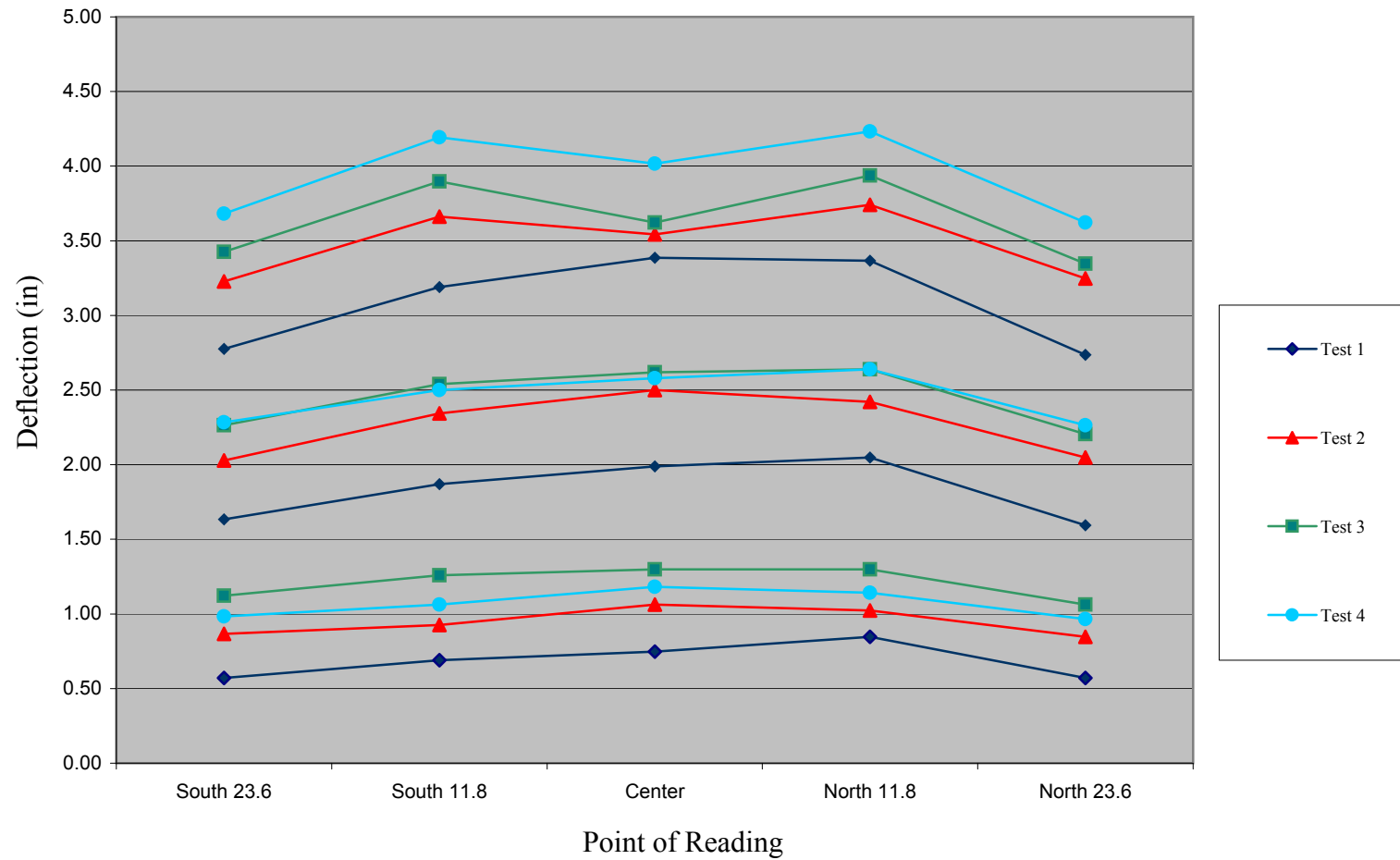


Figure 18. Incremental Deflection for All Four Multi Sheet Test Series of Vinyl Sheet Pile with Interlock Placed in Tension - 18" Loading Maximum

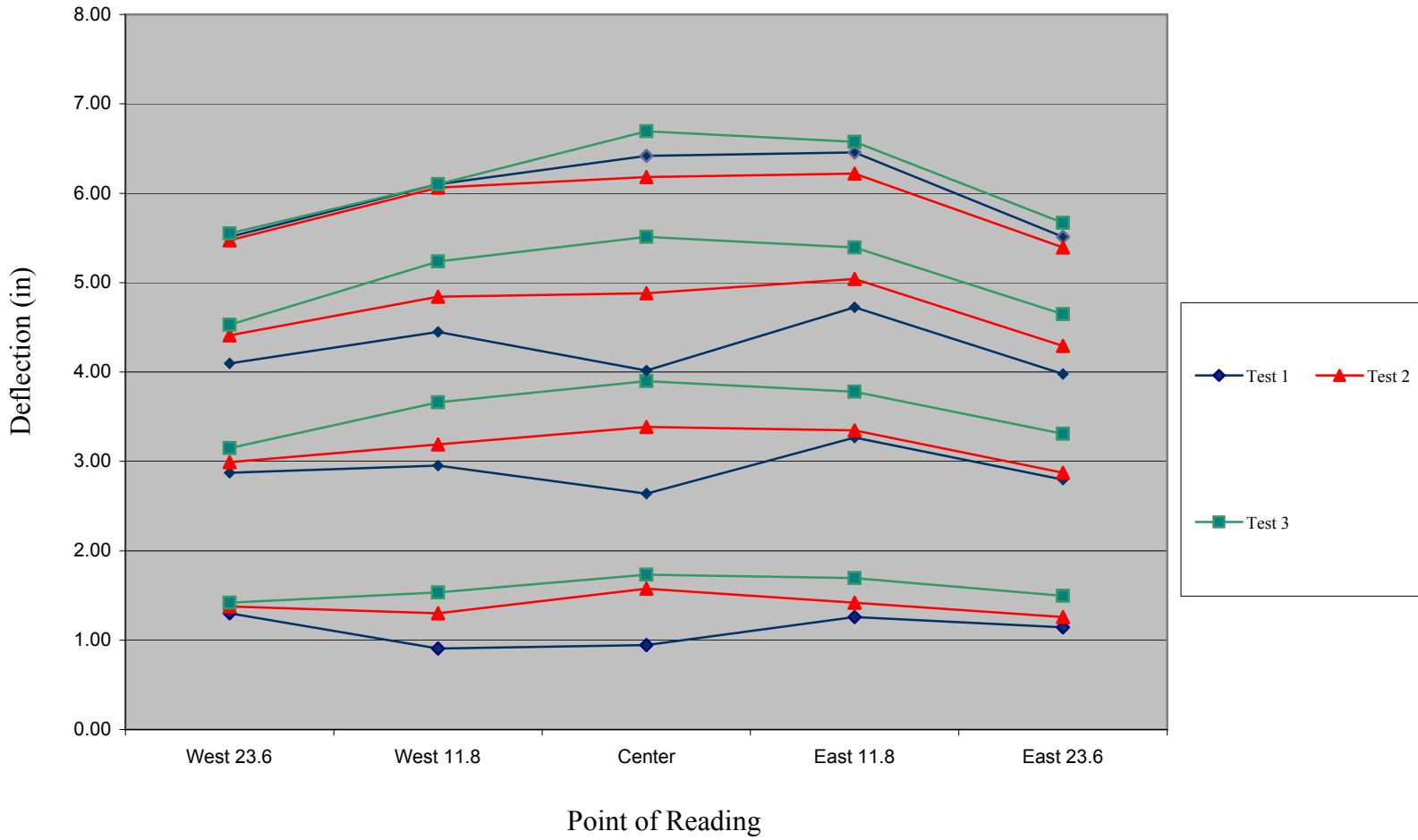


Figure 19. Incremental Deflection for All Three Multi Sheet Test Series of Vinyl Sheet Pile with Interlock Placed in Compression - 24" Loading Maximum

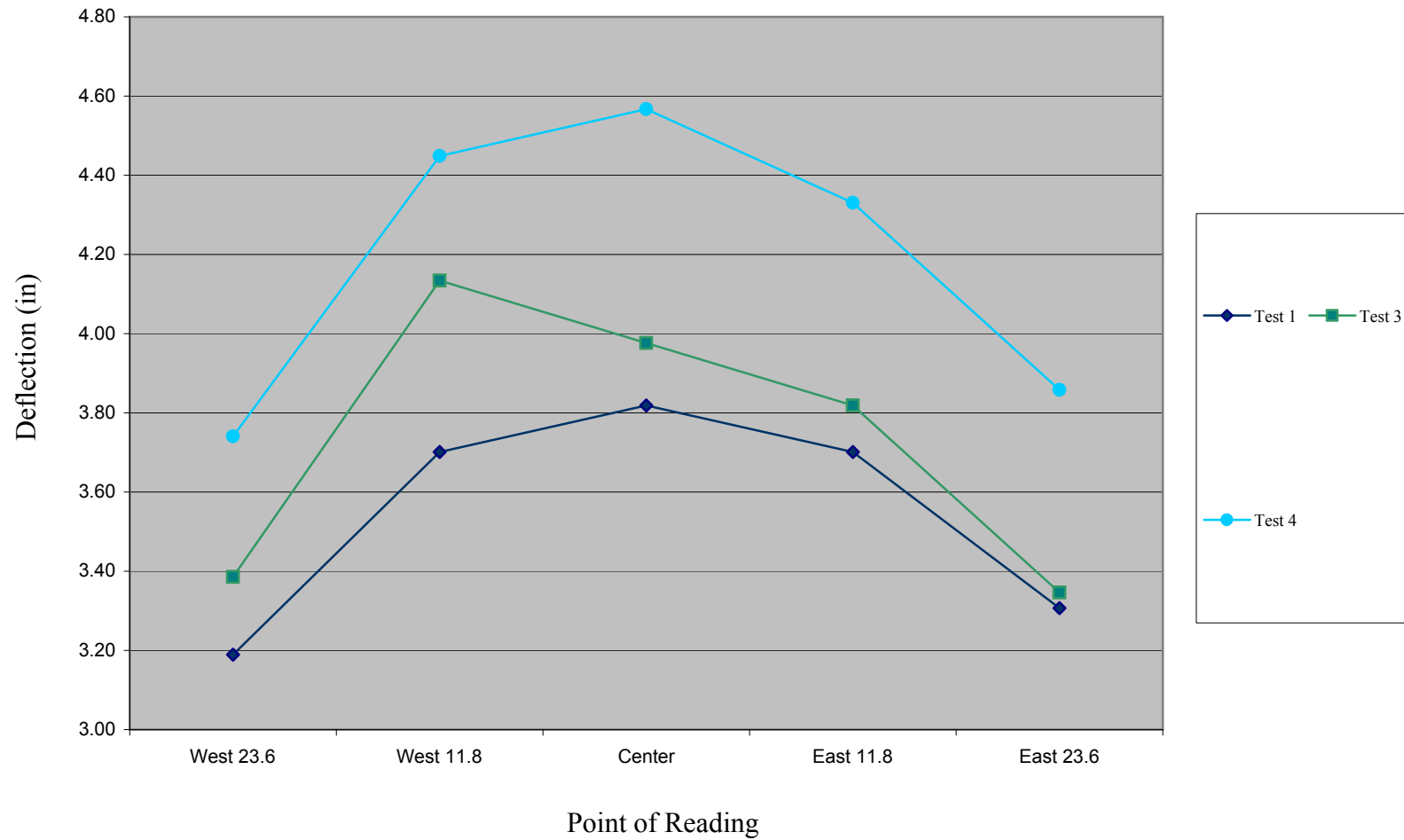


Figure 20. Incremental Deflection for Multi Sheet Test Series - Interlock-in-Compression - 18" Sand Fill

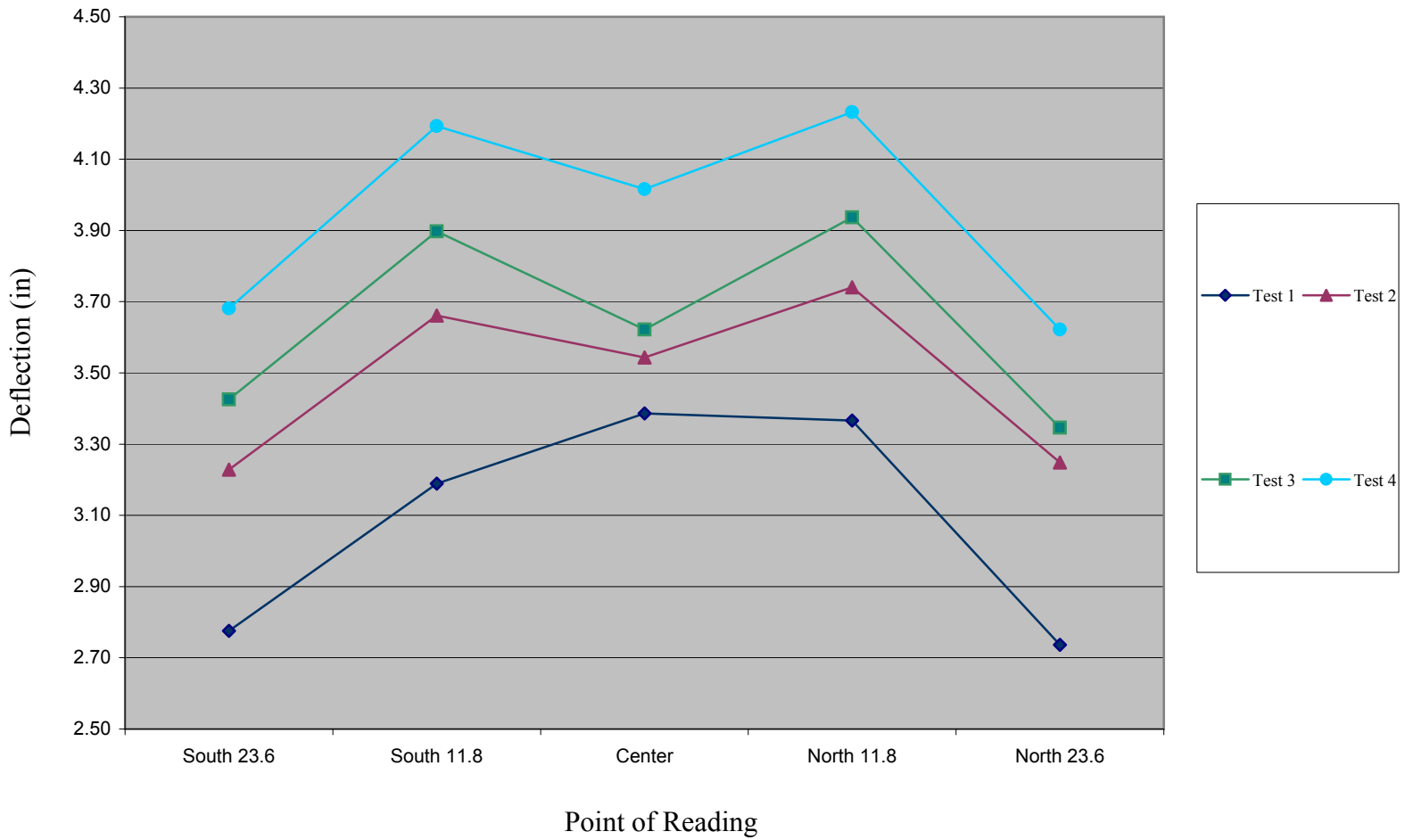


Figure 21. Incremental Deflection for Multi Sheet Test Series - Interlock-in-Tension - 18" Sand Fill

frame will stress the material beyond the prior deflection (Test J) because of a lack of recovery time for the crystalline structures.

An exception to this trend of test J+1 providing a larger deflection than test J was observed during the fourth IIT test in Figure 22 for a 6" loading. In this figure the deflections measured during test four were less than those measured during test three. A decrease in deflection of about 10% was observed during test four compared to that of test three. The main difference between the test three and four of the IIT series was the allotted time of recovery. The allotted time of recovery is the time between tests in which the sheets are not loaded. Between IIT tests one, two and three the sheets were allowed to recover for only one week. Because of scheduling conflicts between tests three and four the sheets were allowed to recover for three weeks. During recovery, which is believed to be time dependent, it is believed that crystals which ruptured initially during loading may be reforming. The length of recovery is believed to have an effect on the amount of reforming which occurs. These results seem to support the idea that the time between loading (the recovery period) has an effect on the sheet stiffness.

It was also observed that after each test, the sheet piles did not return to their original pre-test deflection datum but rather retained a no-load deflection of 1/8". Kim and Gilbert (2004) proposed that the crystal fraction (10% by volume) has an effect on the structural characteristics of PVC. Yarahmadi et al. (2003) showed evidence that the PVC crystals are oriented during the extrusion process. It is believed that during testing we saw evidence of these effects. Much of the initial recovery is thought to be caused by the release of stress in the amorphous PVC chains. However, because of possible crystal rupture it is theorized that the sheet cannot return to the original pre-test deflection.

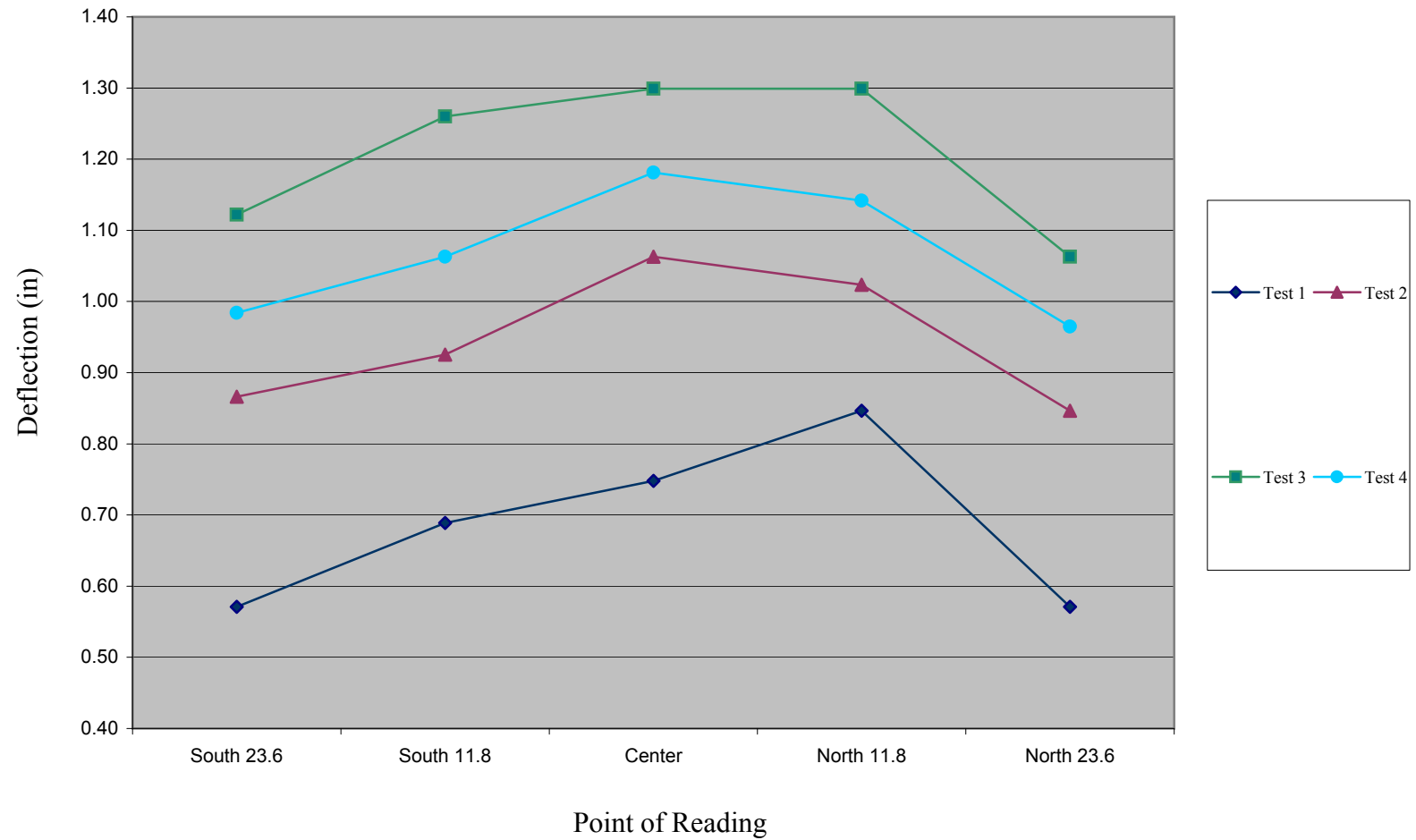


Figure 22. Incremental Deflection for Multi Sheet Test Series - Interlock-in-Tension - 6" Sand Fill



It is important to address the shapes of some of the data curves describing deflection for these tests. In Figures 20 and 21 various tests produced unexpected deflections at the center points of the curve. For tests two, three and four (Figure 21) the deflection at the center most point was less than that measured 11.8" from the center. Based on traditional beam theory the center most point would be the point of maximum deflection. Two major factors have been identified that affect the measured data points: position of measuring laser on the concrete grade and rotation of sheet pile in the frame. The base of the laser was rested on the concrete grade to measure the distance to the sheeting. It was noticed that if the laser was rotated no more than 1/16" a significantly different measurement was observed. The undulations in the concrete grade which existed could produce such a tilt in the meter if not careful. The sheets themselves were also capable of slight rotation during loading, thereby resulting in a change in distance from the concrete floor to the deflected sheet pile. It was observed that during loading a 3/8" vertical difference was measured between extreme points on the flange of the center sheet pile. Set points were defined on both the concrete grade and sheet pile to measured deflections of the sheets. These set points were used during each test and were used to eliminate as much as possible any variability in measurements caused by user error. Based on the results of these tests, it would be prudent to advise any future tests be conducted by taking data points across the face of the sheeting and averaging the numbers to get a more accurate view of how the system is acting globally. This method was used during the single sheet tests and the results are more indicative of a traditional beam deflection curve.

It was previously assumed that having the interlock in tension would provide some benefit in limiting deflection. However, the data does not appear to bear this out. In Figure 23, are shown the average deflection data from test 1 for both the IIC and IIT series for 6", 12" and

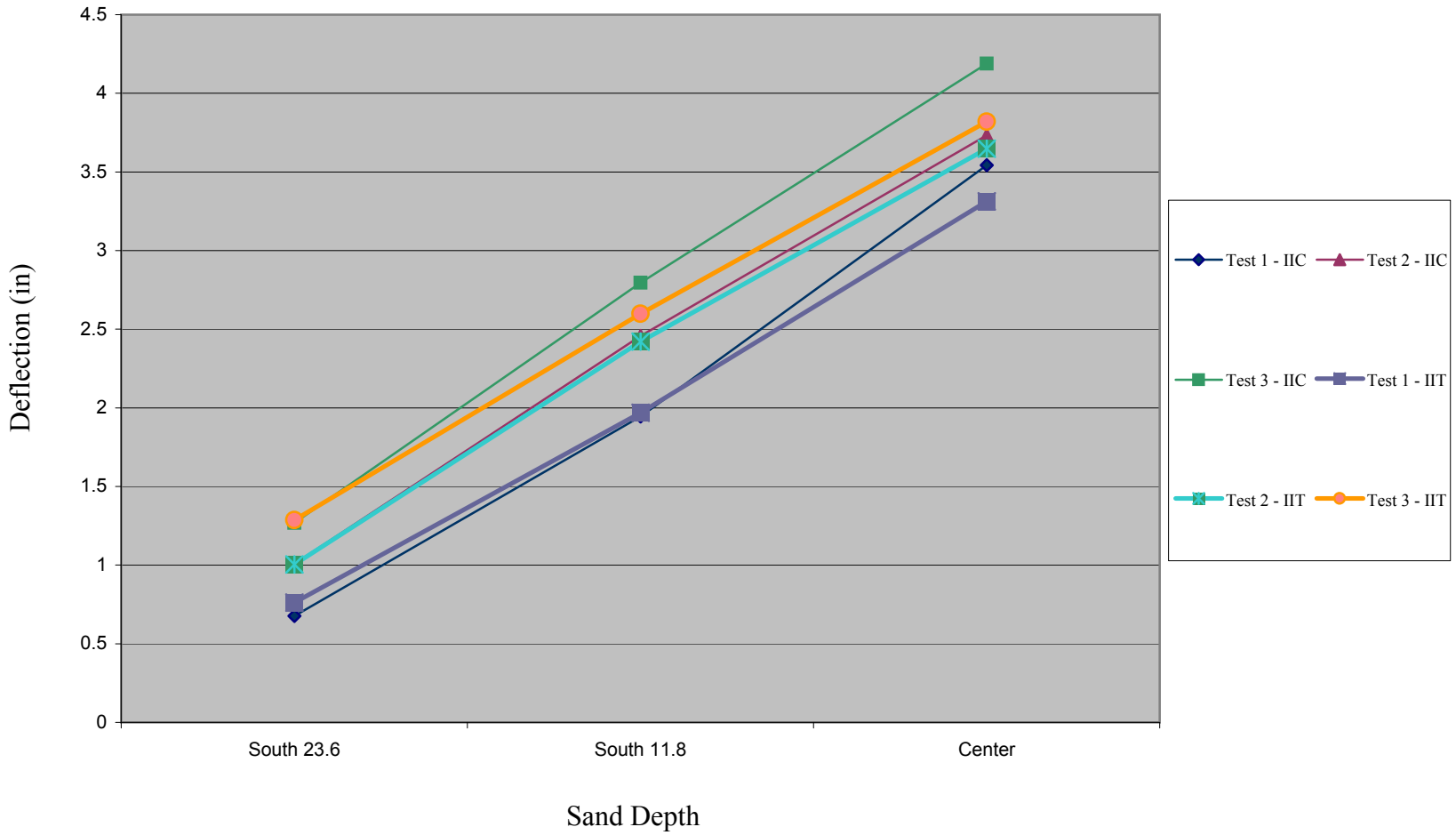


Figure 23. Comparison of Average Deflection of PVC Sheet Pile for Interlock-in-Compression (IIC) and Interlock-in-Tension (ITT) Test for 6", 12" and 18" Sand Depths

18” of sand. Each set of deflection curves show little difference between sheets loaded in IIC versus sheets loaded in IIT.

Current information in the literature indicates that time of exposure to UV radiation should not affect the material properties of PVC. In Table 2 are shown deflection data for tests in which a variation in exposure to UV radiation occurred. In Table 2 both of the 18” loading tests were conducted using PVC manufactured a short time prior to testing while the sheet pile used in the 24” loading test were manufactured approximately one year prior to testing. During that one year period the PVC sheet pile was stored outside and exposed to UV radiation. For both the 18” IIC and IIT tests significantly less deflection was observed during these two tests than those of the 24” IIC test. During these tests the PVC that had been exposed to UV radiation had, on average, 30% more deflection than the PVC which had not been exposed to UV radiation. The only notable differences between these sets of sheets were their production dates and exposure to UV radiation. Rabinovitch et al. (1993) noted that exposed PVC samples showed little to no reduction in mechanical properties such as tensile modulus of elasticity. However, this data appears to show the possibility that UV exposure could have some effects on PVC strength. Based on this study, too little data exists to make a conclusion about the effects of UV exposure. For a design methodology to be effective it must accurately predict the behavior of its subject to within an acceptable range. Figures 24 and 25 compare the average initial deflection to theoretical calculated deflection curves. Theoretical deflection curves were plotted assuming the sheets to be simply supported beams with both a uniform load and triangular load, as shown in Figure 13. The triangular load is caused by the sheets deflecting during loading. The magnitude of the triangular load was estimated from average deflection in the sheets. Superposition was

Table 2 - Comparison of Net Deflection for Multi Sheet Testing - Initial Loading			
	Net Deflection (in)		
	18" (max.) Compressive Loading	18" (max.) Tensile Loading	24" (max.) Compressive Loading
	Produced: July 25, 2010		Produced: June 13, 2009
6" Loading	0.686	0.678	1.11
12" Loading	1.826	1.946	2.906
18" Loading	3.094	3.544	4.252

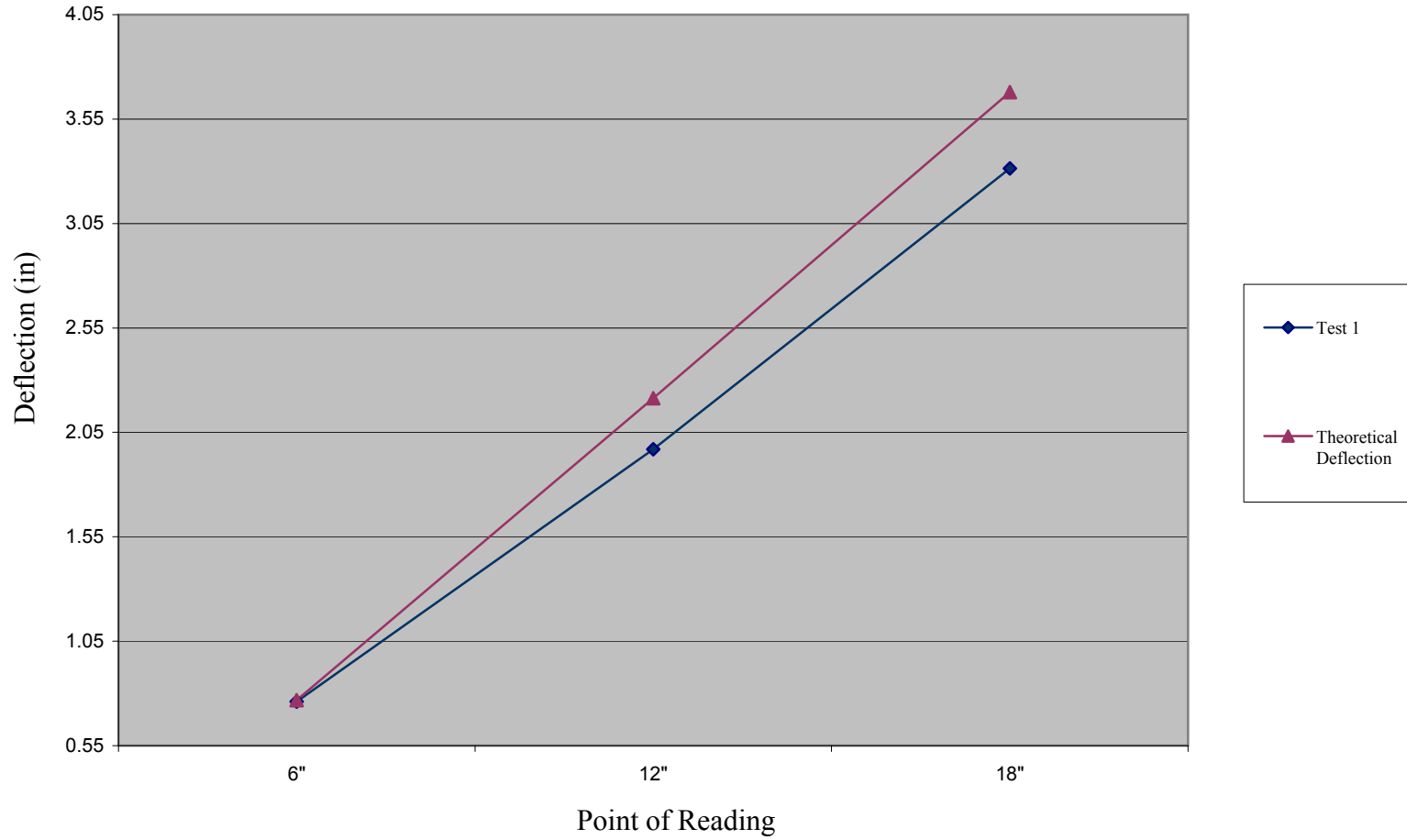


Figure 24. Comparison of Initial Deflection for Interlock-in-Tension Test - 1st Series - to Theoretical Deflection Using a Modulus of Elasticity of 380,000 psi

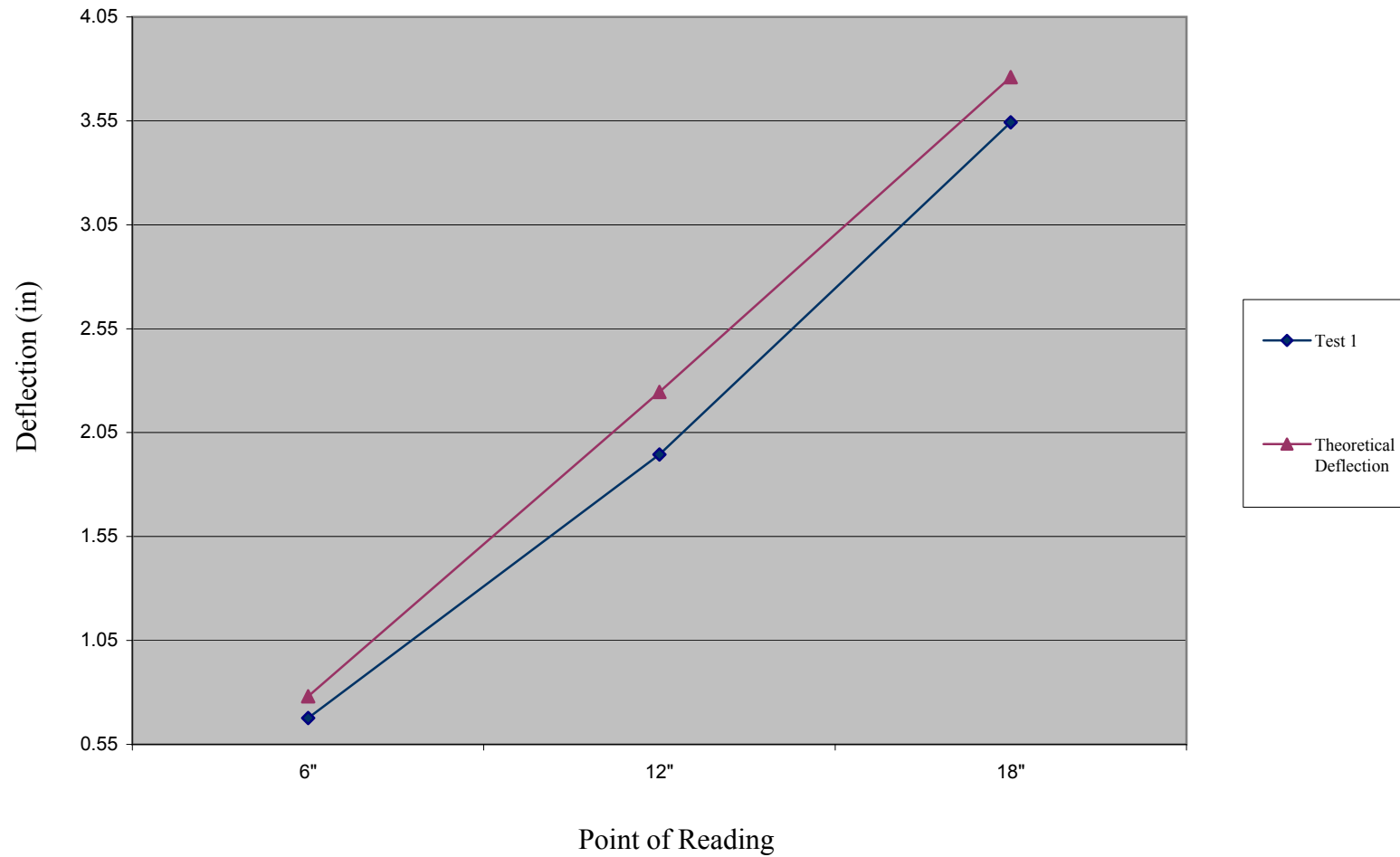


Figure 25. Comparison of Average Deflection for Interlock-in-Compression Test - 1st Series - to Theoretical Deflection Using a Modulus of Elasticity of 380,000 psi

then used to form an aggregate deflection. The simply supported uniform load deflection equation is:

$$\Delta = 5 * w * l^4 / 384 * E * I \quad (3)$$

where  $w$  is the magnitude of the uniform load,  $l$  is the span length,  $E$  is modulus of elasticity and  $I$  is the area moment of inertia. The triangular load deflection equation is:

$$\Delta = w * l^4 / 120 * E * I \quad (4)$$

where  $w$  is the magnitude of triangular load at mid-span,  $l$  is the span length,  $E$  is modulus of elasticity and  $I$  is the area moment of inertia. An  $E$  of 380,000 psi was used for all theoretical calculations. This value of  $E$  is commonly used by the various vinyl sheet pile manufacturers to predict deflection in these types of wall systems. Both Figures 24 and 25 indicate that the initial measured deflection was less than the theoretical deflection as predicted by the beam equations. This would indicate that the actual modulus of elasticity in these sheet piles are greater than 380,000 psi. Under first review, these results support the vinyl sheet pile industry's use of 380,000 psi as an appropriate initial modulus of elasticity.

Since PVC behaves in a viscoelastic manner it is important to address creep deflection. This deflection would be caused by the same mechanism that Alfrey et al. (1948) described. To this end, initial deflection data and deflection after seven days of constant loading from all three tests on Frame 1 and 2 were compared both graphically and by table. Table 3 shows the calculated apparent modulus and how it decreases over time. All sheeting showed a significant reduction in modulus of elasticity over the seven day period with the 24" IIC test having the lowest modulus of elasticity over time. Van de Kuilen (1999) used laboratory data on C-Loc PVC sheet piling to develop a reduced modulus of elasticity over time. Based on this data he indicated a modulus of elasticity of 362,250 psi would be apparent after seven days of loading.

Table 3 - Comparison of Modulus of Elasticity of the Full-Scale PVC Sheet Pile Tests After Initial Loading and Over Time								
	18" Loading - Interlock in Compression		24" Loading - Interlock in Compression		18" Loading - Interlock in Tension		Single Sheet Loading	
Stress in Sheet (psi)	2,780		3,964		2,723		1,515	
Calculated Modulus - 1st Test (psi)	Initial	7 days	Initial	7 days	Initial	7 days	Initial	4 days
	416,000	354,000	355,000	291,000	459,000	352,000	410,000*	324,000
% Change	-14.9		-18.0		-23.3		-21.0	
Modulus Loss per Day (psi/day)	8,857		9,143		15,286		12,286	
% Change from 7 day Modulus - 362,250 psi (Van de Kuilen, 1999)	-2.3		-19.7		-2.8		-10.6	

\* Assumed from previous full-scale sheet pile compressive testing as to initial modulus of elasticity.



This modulus of elasticity agrees closely with the modulus of elasticity calculated from the IIC 18" and IIT 18" tests after seven days load duration.

Figures 26 to 28 show the comparison of measured creep deflection from all three multi sheet tests to the predicted creep deflection calculated by Van de Kuilen's equation, (2). Using this equation to determine creep coefficients that modify predicted deflections, the mid-span deflections after seven days should be 35 to 40 percent larger than the initial deflections. For the IIC experiments, the seven-day deflections were approximately 20 to 25 percent larger than initial deflections. For the IIT experiments, Van de Kuilen's technique would once again predict a 35 to 40 percent increase in deflection. For the IIT experiments, an increase in deflection of 30 percent was observed over seven days. Van de Kuilen's creep coefficient is based upon bench scale lab tests and is not based upon full-scale testing.

## 5.2 Deflection of Single Sheet Pile Testing

The results of the single-sheet tests were disappointing and seem unreasonable when compared to either the literature or previous tests. Unlike the multi-sheet tests, the deflections measured for the single sheets tests were much smaller than expected and act like a wide beam loaded with a uniform load of 540 lbs/ft. The lack of direct correlation from the load in the loading box to the predicted deflection of the sheeting was unexpected at the time of initiation of the test. Based on this data MOE values of almost 800,000 psi were predicted from this data. These values are almost twice those of values found in the literature and those previously calculated from the multi-sheet testing. If a MOE value of 410,000 psi is used, which was calculated in the initial loading in the multi-sheet tests, a uniform load of only 190 lb/ft would produce the magnitude of deflections measured during these tests. It is believed that during testing the sand actually behaves in an arch action within the narrow box and instead of loading

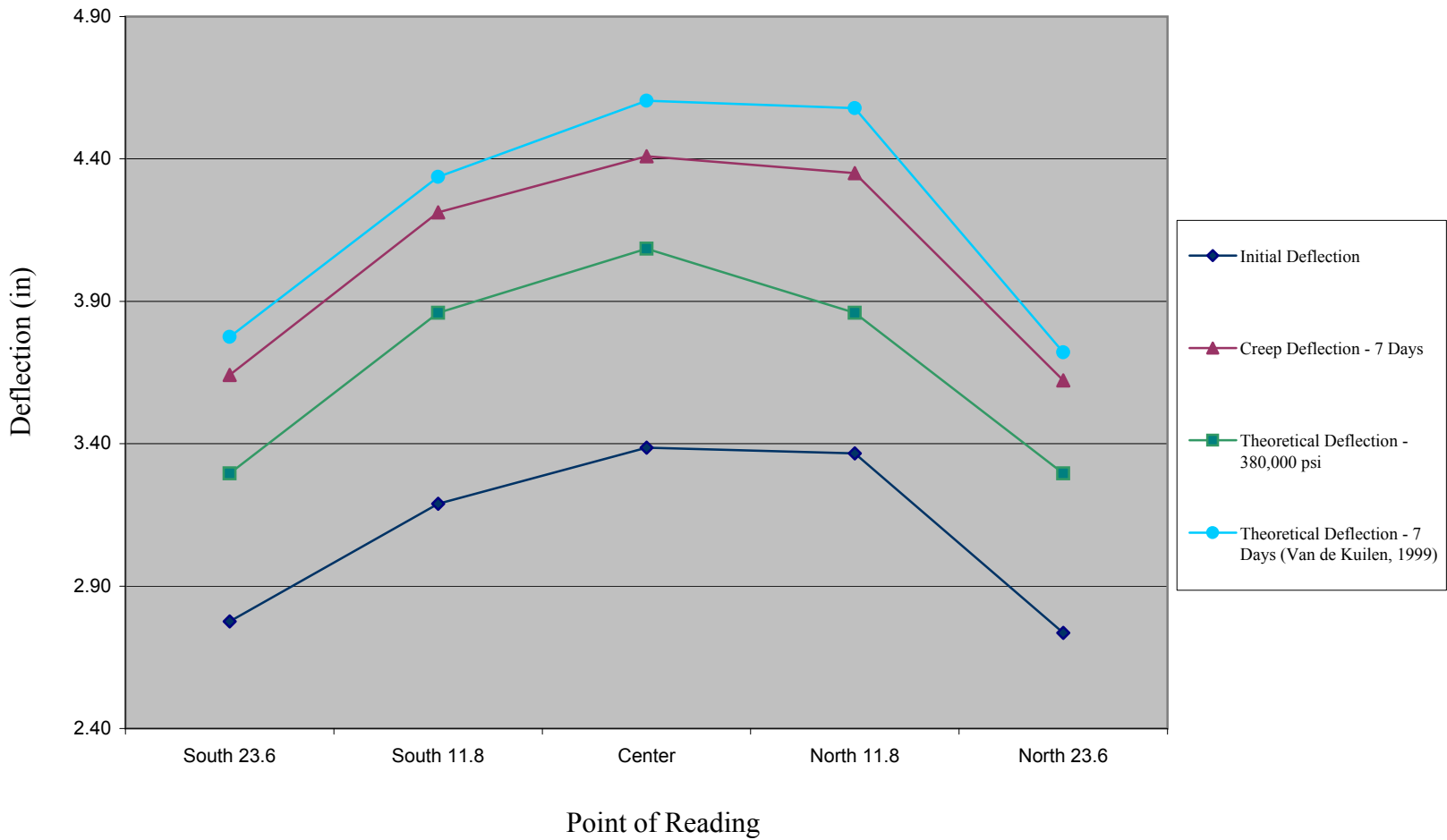


Figure 26. Initial Deflection and Creep Deflection After Loading as Compared to Standard Theoretical Deflection and Predicted Creep Deflection - 18" Final Loading with Interlock in Tension

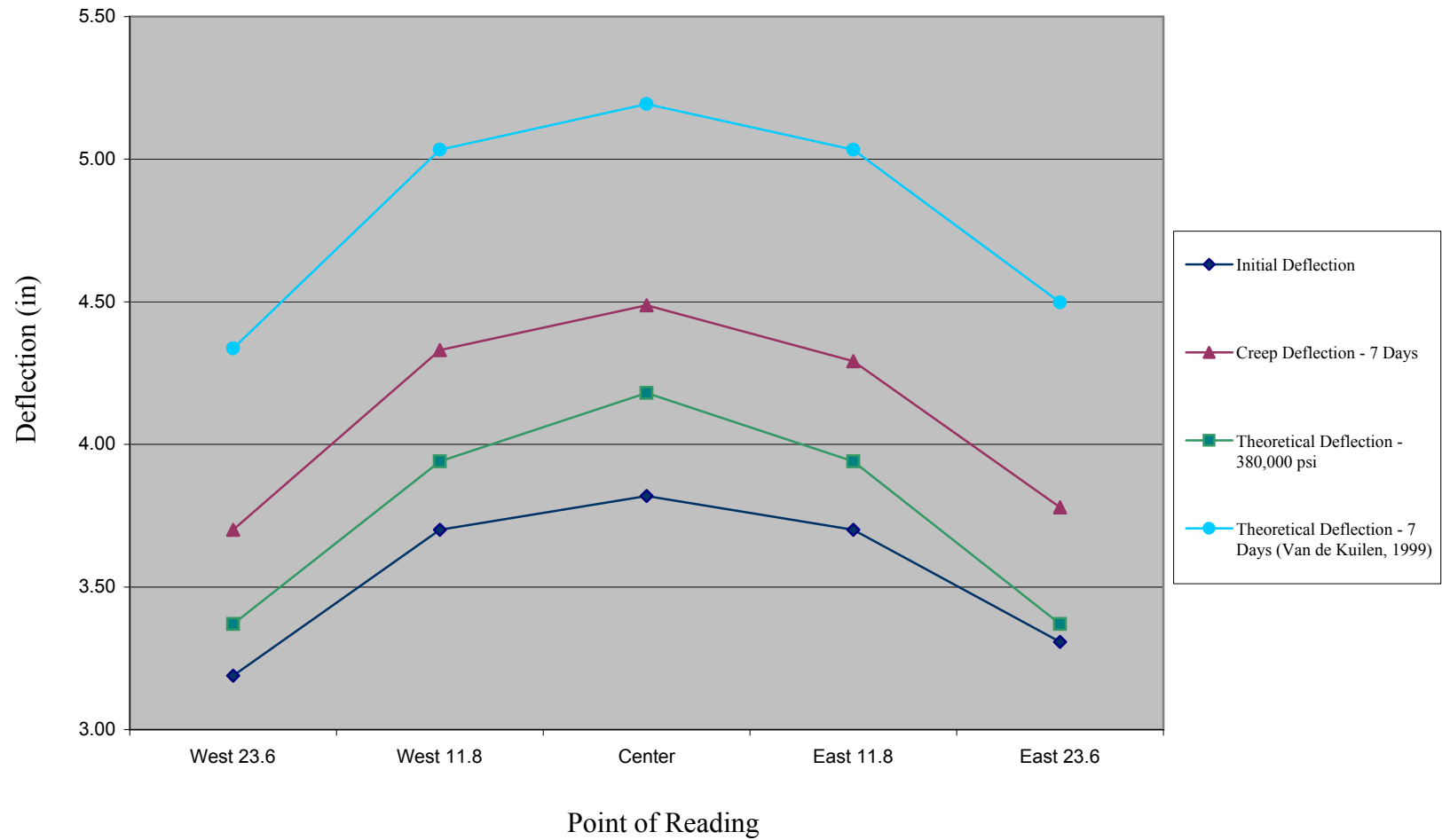


Figure 27. Initial Deflection and Creep Deflection After Loading as Compared to Standard Theoretical Deflection and Predicted Creep Deflection - 18" Final Loading with Interlock-in-Compression

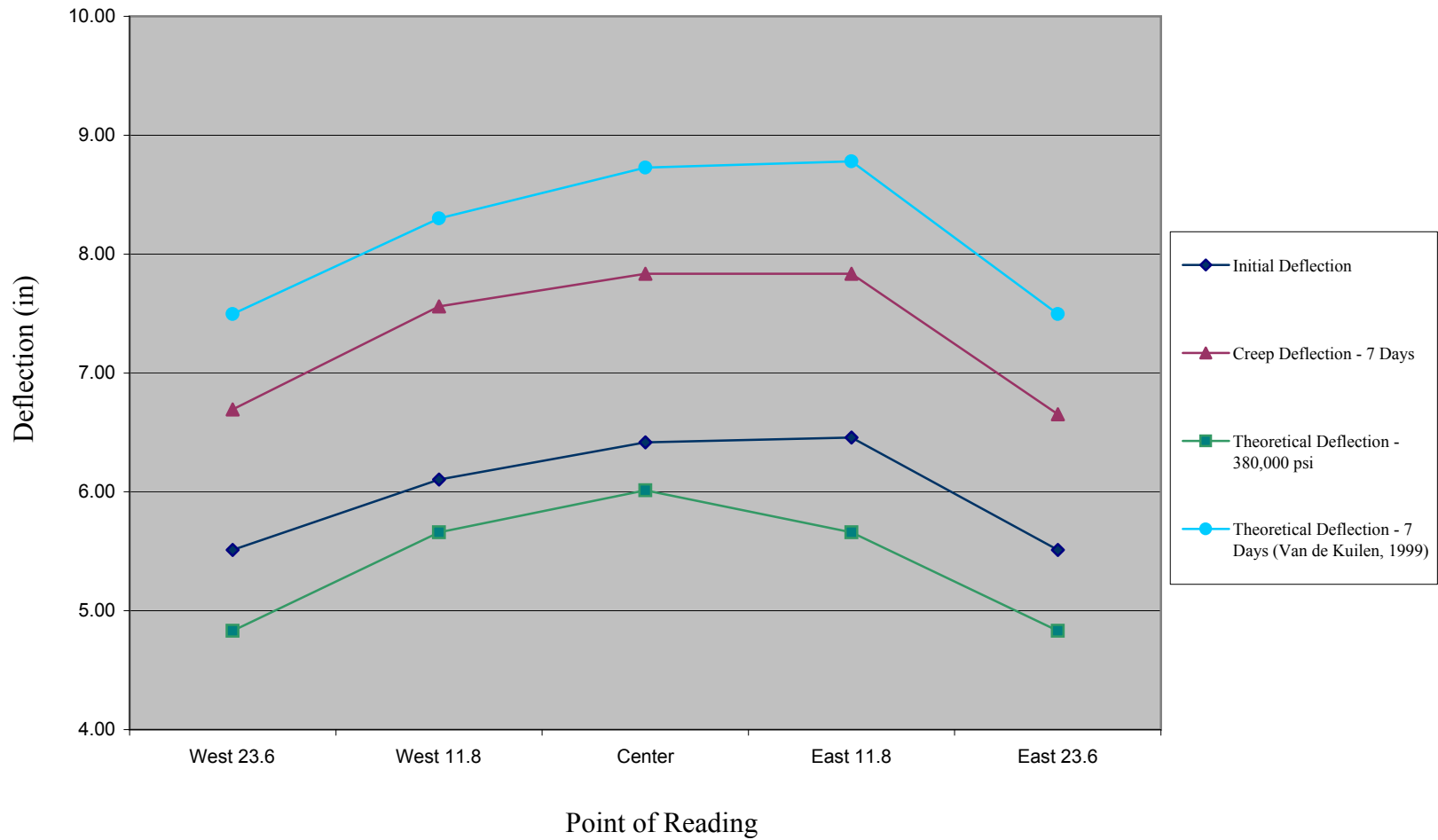


Figure 28. Initial Deflection and Creep Deflection After Loading as Compared to Standard Theoretical Deflection and Predicted Creep Deflection - 24" Final Loading with Interlock-in-Compression

the pile the sand is actually loading only the sides of the box. The angularities of the sand particles allow individual particles to stack against neighboring particles. This results in the internal angle of friction, the largest angle over which a granular soil can carry a shear load. The sand particles can only act over a small distance before gravitational forces overcome the friction force thereby disrupting the internal arch structure. Other than to use this data as a qualitative instrument for general deflection conformation, all data from this series of tests was excluded from this thesis.

### 5.3 Strain Data from Full-Scale Sheet Pile Testing

Experimental strain data, along with bench scale testing on other PVC profiles, are summarized in Table 4. Full-scale test strains measured after 100 hours of testing and at approximately 4000 psi stress were compared to those measured by Findley (1987), Northstar (SGI, 2007a) and Everlast (SGI, 2007b). The strain data from the Northstar and Everlast studies were based on test results of PVC “dog-bone” samples taken from PVC sheet pile, while Findley tested strips collected from PVC pipe products. Both the Northstar and Everlast samples were from PVC sheet pile with thicker profiles than those used in these experiments. The experimental strain data measured during field testing was larger than that measured by Findley (1987) while smaller than the strain measured using the sheet pile “dog-bone” samples.

This is possibly explained by the compounding of the individual vinyl substrates. Findley (1987) used unplasticised PVC in his creep experiments. This would result in a more rigid compound with less elongation potential. When PVC sheet pile is manufactured, as a general rule, it is modified by the addition of small fraction of plasticizers. These plasticizers act as impact modifiers to allow a softening of the material which in turn produces a product with improved handling of impact forces. This could be a plausible reason that the strains from the

Table 4 - Total Strain Comparison of Full-Scale PVC Sheet Pile Testing Versus Bench Testing on Various PVC Samples			
Source	Stress (psi)		Total Strain @ 100hrs (%)
Experimental Strain 24" Loading	3,964	1st Test	1.42
	3,940	2nd Test	1.24
	3,999	3rd Test	1.29
Northstar Vinyl Sheet (SGI, 2007)	4,000		2.12
Everlast Vinyl Sheet (SGI, 2007)	4,000		1.89
Findley, 1987	4,000		0.997

sheet pile samples are larger. Also, the Northstar product was a mono-extruded product that used a higher fraction of recycled materials in its construction. Based on Arnold et al. (1996) impurities can have an effect on product strength and ductility. The differences between the “dog-bone” samples and the full-sheet piles could also be caused by geometric differences. The “dog-bone” samples are a sheet while the sheet pile has a “folded” geometry. This geometric difference is thought to contribute smaller strains.

While strain data was collected during the single sheet tests, these results of these tests were considered invalid because of the erratic fluctuations in strain measurements.

## 6.0 Conclusions

This project was initiated as a first step to gain better insight into the behavior of polyvinyl chloride sheet pile as a system and eventually apply these results to develop a design methodology that would include issues inherent to synthetic materials. The literature was reviewed to develop an understanding of what design systems were currently being utilized as well as the material properties of polyvinyl chloride materials. Experiments were conducted to determine how the sheeting acts under a controlled loading situation and what deflections would occur over time. The tests centered on the overall deflection of the sheets and the accompanying strain.

Based on current literature, design methods for synthetic sheet pile are largely borrowed from steel sheet pile design, but some headway has been made in address issues relevant only to viscoelastic materials. This is largely accomplished by setting a maximum limit to the allowable bending design stress to preclude any significant creep effect occurring within the material. It is also recommended that a minimum stress approach, via cell classification, be used. The cell classification system provides designers with nominal design values for each stress conditions. While this approach can be used in material selection it does preclude manufacturers from testing products and ensuring that this nominal stresses are met. PVC is a well studied material and its mechanics under varying load and time are significantly documented. Descriptions of the macromolecular structure of PVC were available as were data on the creep functions of the material. However, most of the information found on PVC does not involve testing of these materials when used as a structural shape.



The experimental data was shown to agree with conventional theory of PVC mechanics in relation to creep deflection and recovery. As the time frame between testing was allowed to increase (increase in recovery time) an increase in the rigidity of the sheet pile was observed. For these tests the application of a creep deflection coefficient calculated by Van de Kuilen (1999) predicted larger deflection than those measured during these experiments.

Based on these tests it is not apparent that one orientation of the interlocks should be preferred over another. Positioning the interlock in compression was not an advantage over positioning the interlock in tension. It was previously assumed that having the interlock in tension provided some benefit in limiting deflections. However, the data does not bear this out.

Strains measured during full-sheet testing of the PVC sheet piles were greater than those previously measured by Findley (1987). Findley's collected strain data on samples of unplasticized PVC. The sheets used in these experiments contain small amounts of plasticizers (<2%). These additives tend to make the sheets more impact resistant which in turn increases the ductility of the sheets and the ability of the sheets to stretch. Everlast has tested PVC samples, cut from PVC sheet piles, at a commercial testing lab to determine total strain over time. The samples used by the test lab were a "dog-bone" shape cut from the pile. The experimental strain data from these experiments, for tests using the entire sheet pile, were smaller than those measured by the testing laboratory. While variations in formulation could be one cause for this difference, geometric differences could also be the cause of these differences. The sheet pile has a folded geometry and is not one long flat sheet.

In general, this project has provided further data to compare against known values and equations. These items may be incorporated into a design methodology in future iterations but

further testing should be undertaken to gain a more complete data set in relation to various stresses, conformations of sheeting and longer time duration.

## 7.0 Implications for Future Research

The construction of a design methodology for synthetic sheet pile based on addressing the viscoelastic nature of polymers will require more extensive research and field verification.

The most direct areas that should be investigated are:

1. Creep deflection at operational stresses and extreme stresses for longer periods of time (one year and greater)
2. Changes in geometry of sheet under operational and extreme stresses
3. Suitable forensic tools that can be used during after-failure analysis
4. Deflection of synthetic sheet pile in the field for model verification
5. Reception by industry and associated engineering support

The models used for many of these efforts will need to be empirically determined. This will require significant amounts of data on deflection, creep deflection and apparent modulus of elasticity be made. The experiments in this study should be repeated for data verification and further experiments with a variety of synthetic sheeting should be undertaken to develop an industry-supported consensus design process.

These efforts should be put forth to the synthetic sheet pile industry to gain as much support as possible. With such a diversity of sheet geometries and company specific PVC compounds, only an industry wide program has the hopes of establishing national criteria for the design with synthetic sheet pile.

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