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# Examination of Mechanical Test Methods for Pultruded Sheet Piling

by

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## Abstract

Pultruded FRP sheet piling is increasingly being used to construct structures such as retaining walls. With the increased use and interest in these pultruded profiles comes the need for tests to characterize the mechanical properties of these sections. The need for standardized tests of these materials has also been cited as being necessary to expand the use of composite pilings. However, at this time, standard mechanical test procedures have not been established for sheet pile profiles. In this paper, various test methods intended to characterize these profiles are examined and data from these test methods are evaluated in order to identify methods that can be used to successfully test these materials.

## Introduction

Sheet piling materials are exposed to harsh conditions in typical waterfront applications. Materials used in these applications must withstand corrosion, high loads, and even attacks by marine organisms. The deterioration of wood, concrete, and steel piling systems has been reported to cost military and civilian users approximately $1 billion annually [1]. Fiber reinforced plastic composites offer excellent properties to address the needs in waterfront environments, and pultruded FRP composites are increasingly being used in these applications.

The use of pultruded sheet piles is still, however, a developing application for this material. A U.S. Army Corps of Engineers Construction Engineering Research Laboratories (USACERL) technical report cited the lack of standardized test methods as one of the technical barriers that must be overcome for FRP composites to be more widely accepted for the U.S. civil engineering infrastructure and construction industry to expand the use of composite pilings for marine and waterfront applications. This (USACERL) technical report was issued in 1998; however, standardized test methods for these structural materials still have not been established. ASTM International established the D20.20.04 Committee on Systems for Marine/ Waterfront Applications, and this committee held its initial meeting July 23, 1996 [1]. A search of the ASTM website indicates that the D20.20 Plastic Products Subcommittee has no standards related to FRP sheet piling and one related proposed new standard, WK 2501 Standard Specification for Polymeric Piles, which has been in development since August 18, 2003. However, the scope of WK 2501 states that this specification is "only applicable to individual polymeric pile products. Sheet pile and other mechanically connected polymers pile products using interlocking system are not part of this specification." WK10050 Full Section Load Test for the Z-shape Sheet Piling is a work standard that was initiated by the D20.18 Subcommittee through the D20.18.04 Pultruded Shapes Task Group. This work standard specifically addresses the full-section testing of Z-shaped pultruded sheet piling; however, it is still early in the development stage [2].

The asymmetrical shapes typically seen for pultruded FRP sheet piling make testing of this material more difficult than for many other commonly produced structural shapes. However, previous research related to full scale testing of FRP structural shapes does provide a good foundation for research related to full-scale testing of pultruded sheet piling. Only limited published research specifically related to full-sale testing of pultruded sheet piling has been published in the open literature.

A significant amount of research has been devoted to the examination of standard pultruded structural shapes, but less information devoted to the examination of pultruded sheet piling has been published [3, 4, 5, 6]. Flexural testing is a relatively simple test procedure that has the potential to be used to determine EI for sheet piling; however, the open section profile used for sheet piling typically leads to localized buckling failure, and thus invalid flexural properties, if a standard flex test setup similar to the set up used in ASTM D790-03 for coupon testing is used. In 1998, Rutgers University tested sheet piling from three different manufacturers as part of the USACERL Construction Productivity Advancement Research Program. Only a brief description of the testing is provided in this report; however, the need for the use of a "special test fixture" for three-point testing of corrugated sheet piling is noted in the report. A photograph in the report shows the "special test fixture" to be formed by 2 wood two x four's forming a sandwich above and below the sheet pile at the location of the supports [1]. In 2003, Giroux and Shao conducted three and four-point flexural tests of one sheet piling profile. They then used this data with the Timoshenko beam equations to determine EI and kGA for the material. For the flexural testing, Giroux and Shao discuss the use of rigid steel frames to provide lateral confinement of the open section of the sheet piling. A photograph shows these frames located at the supports and load points for the four-point flexural test. In this research a single section of sheet piling was tested [7]. In 2006, Shao conducted four-point flexural testing on two connected sections of sheet piling that were connected using the pin and eye of the profile to increase the width of the section being tested. For this series of tests, flexible metal pallet straps were used to confine the open section of the sheet piling; the straps were spaced 19.7 inches (0.5 m) apart down the length of the beam. From a photograph of the test setup, it appears that round rods were used at the loading and support points [8]. In addition to this published research, manufacturers have also developed their own unpublished, proprietary test methods for pultruded sheet piling.

The objectives of this paper are to examine the use of different test methods with potential for use as a standardized test method for full-scale testing of pultruded sheet piling and to provide experimental data that can be used to compare these methods. As the purpose of this paper is to compare various methods that could be used for full-scale testing of pultruded sheet piling and to demonstrate the differences that can result from the use of different test methods, the mechanical property data discussed in this paper is intended to be used to directly compare the methods but is not intended to be taken as published data to be used for design calculations for this material. In this paper, three-point test methods that can be used to determine the section flexural modulus are examined. The work presented in this paper is an initial step toward an overall goal of providing data that can be utilized as a standardized test method for pultruded sheet piling is established.

## Experimental Procedure

Although the use of flexural testing to obtain load and deflection data that can be used to determine the section flexural modulus and the section shear modulus has been demonstrated by various researchers for commonly used structural shapes as well as for sheet piling, the best method to use for the flexural testing of sheet piling has not been established. To accurately represent the sectional flexural properties of the sheet piling, it is necessary to utilize some type of constraint that will discourage localized buckling and twisting of the section. If this is not done, the behavior shown in Figure 1 is seen at very low loading levels. In this research, various approaches for constraining the sheet piling section during a three-point flexural test and for introducing the load are examined, and the section flexural rigidity (EI) determined from the simple beam equation for three-point loading are compared for each method.

In developing methods to constrain the sheet piling and conduct the necessary flexural tests, a number of desirable test characteristics were identified. Ideally, the constraint method used would not result in damage to the sample being tested, would be easy to set up for different profile geometries, would uniformly but not excessively constrain the sample, would not cause local damage during loading, and would be repeatable. The methods examined in this preliminary examination of flexural test procedures for sheet piling include the use of steel plates with a cutout matching the geometry of the sheet piling profile being tested, the use of flexible plastic straps, and the use of wood supports cut to match the inside profile opening of the sheet piling. The sheet piling profile shown in Figure 2 was used for all testing discussed in this paper. The asymmetric geometry of this section makes the testing of this profile especially challenging..

For each set of tests, a 16 ft long section of sheet pile was used. All tests were conducted at the University of Mississippi using a hydraulically actuated MTS universal test machine using a calibrated 10,000 lbf load cell to measure the load applied and an LVDT on the actuator to measure the displacement of the sheet pile. To avoid damaging the sheet pile sections tested during this preliminary examination of test methods, a maximum load of 950 lb was applied during each test. Samples were loaded at 0.2 inches/minute. For all tests, one inch diameter rods were used as the three-point test fixture supports. For this preliminary examination, a carpenter's level resting on the top of the sheet pile was used to evaluate the degree of twisting and warping that occurred during any given test. This level can be seen in the background of the photograph in Figure 2. For future tests, the use of strain gages is planned to quantitatively measure the strains in the sheet pile.

### Flexural Testing with Flexible Strap Constraints

Flexible plastic straps designed for use as pallet straps were used as constraints for this method. This approach is similar to the constraint approach used by Shao except that plastic straps instead of metal straps were selected for this test method and only a single sheet piling section was tested instead of the two connected sections that were tested by Shao [8]. It was thought that the plastic straps would act as sufficient constraints without damaging the sheet pile as metal straps could. Straps were installed using a hand tightening tool. Straps were located 6" away from center to accommodate the 12 inch wide loading plate used at the center of the simply supported beam, and straps were then placed approximately every 18 inches down the length of the beam. Tests were conducted at support spans of 11.5 ft., 12 ft., 13 ft., 14 ft., and 15 ft. using a single 16 ft long section of sheet pile. Two sets of experiments were conducted using the flexible straps – “Strap” and “Restrap.” The “Strap” set of experiments was conducted first, and three replicate tests were conducted at each span for this set of experiments. For the “Restrap” set of experiments, the straps used for the “Strap” set of experiments were removed, and a new set of straps was installed. The “Restrap” set of experiments was conducted to examine the repeatability of strap installation and testing with a different set of straps. Because each replicate test for the “Strap” set of experiments had been very consistent, two replicate tests were conducted for each span of the “Restrap” set of experiments. As shown in Figure 3, the tests conducted at a given span for both the “Strap” and “Restrap” experiments were very repeatable.

For all “Strap” and “Restrap” tests, a 8” x 24” x 1” steel plate was used as a loading plate at the center of the sheet pile section for the three-point flexural test. A 12” x 24” x 0.25” piece of plywood was used between the steel loading plate and the surface of the sheet pile to protect the surface of the sheet pile from damage.

For comparison, another set of tests, referred to as “WoodStrap” in this paper, was conducted using the same straps as the “Restrap” set, but instead of introducing the load only on the top surface of the sheet pile, a 4.5” thick wood block that had been cut to fit the inside contours of the sheet pile section was placed under the loading nose. To ensure that the wood uniformly contacted the bottom surface of the sheet pile, a layer of sand approximately 0.5” deep was placed under the wood to uniformly distribute the load to the sheet pile. The shape of the wood block is shown if Figure 4. This experiment was conducted to compare the effect of distributing the load over the entire cross-section of the sample instead of just applying the load to the top surface.

Finally, a set of experiments was conducted with another sheet pile sample using plastic straps to determine the effect of the strap tension, the strap spacing, and the number of straps used. The load was applied the same as in the “Strap” and “Restrap” experiments, that is directly to the top of the sheet piling. The only difference in these comparison tests with the “Strap” and “Restrap” experiments was that a wooden 2x4 block cut to fit the contours of the inside of the sheet piling was placed in the sheet pile while the straps were tightened, every 18” down the length of the pile. The use of the wood blocks for this set of “StrapBlock” experiments was intended to help ensure that uniform tension was applied to the straps and to limit the amount of tension that could be placed on each of the plastic straps. With no wood block present, the straps could be tensioned so much as to squeeze the sheet piling into a smaller opening at the top which would obviously change the beam stiffness. With the wood blocks inserted into the open contours of the sheet piling (Figure 4), the plastic straps could only be tensioned to the point where the wood blocks resisted any more tensioning thereby better maintaining the original shape of the sheet piling. It is known that devices to measure strap tension are available, but due to the cost of these instruments, it was decided that the wood blocks would provide a low-cost alternative for these initial experiments.

The “StrapBlock” experiments were followed by the “StrapBlockCut#” experiments where the “#” indicates how many straps were cut symmetrically from each side on the loading point. The first test to determine the effect of the number and spacing of the straps was based on cutting one strap symmetrically from each side of the sheet piling and thus was labeled “StrapBlockCut1”. It was felt that the strap nearest the outside span supports was useful so the first strap to be cut was the second strap in from the end of the beam. Thus, one strap was left near the location of the outside span supports, but the first strap in from that outside strap was removed. Flexural tests were then conducted and repeated at spans from 12’ to 15’ at one foot intervals. For the “StrapBlockCut2” experiments, another strap was removed moving in toward the center of loading nose. With two straps cut, the spacing between the outside strap near the span support and the first strap was approximately 54”. For “StrapBlockCut3” another strap was cut away moving toward the inside of the loading nose. With three straps cut symmetrically from each side of the sheet piling, only the outside strap near the support span remained as did the strap next to the loading nose plate. However, there were no straps for the approximately 72” of distance between these two straps. Since only the outside straps near the support spans and the inside straps near the loading nose were left, it was decided not to cut any more straps since it was known that with no straps, the buckling of the beam prevented proper testing.

### Flexural Testing with Steel Plate Constraints

Steel plates shown in Figure 5 were used as constraints for this test method. Plates were located 4.5” away from center to accommodate the 8 inch wide loading plate at the center of the simply supported beam, and plates were then placed every 18 inches down the length of the pile. Even when care was taken when installing the steel plates, the plates caused scarring of the sheet pile surface. Also, audible “pops” and “cracks” associated with composite damage were heard during the tests that used the steel constraint plates, but noises were not heard during the testing using the flexible straps.

The setup of the flexural test with the steel plates is shown in Figure 6. To avoid localized damage from the steel plates at the center loading point, the two center plates formed a 9 inch wide cavity that was filled with sand as shown in Figure 7. All-thread was used to connect the plates, and duct tape was used to seal the cavity and contain the sand. Load was then applied to the surface of the sand via a 8” x 24” x 1” steel plate with a 12” x 24” x 0.25” piece of plywood used between the steel loading plate and the sand. The sand was used to distribute the load across the surfaces of the sheet pile instead of concentrating the load at the location of the steel plates. When the load was concentrated at the steel plates, localized damage to the sheet pile occurred. As with the “Strap” and “Restrap” sets of experiments, tests were conducted at support spans of 11.5 ft., 12 ft., 13 ft., 14 ft., and 15 ft. using a single 16 ft long section of sheet pile for the “Plate” experiments. Two replicates tests were conducted for each of these spans. As seen in Figure 8, differences were seen for the replicate tests for the “Plate” set of experiments. The use of the sand did allow more uniform distribution of the load, but the setup for these tests required that the sand be initially loaded to fully compress the sand prior to conducting tests to record load vs. displacement data for the sample. Also, set-up for the sand was more time consuming than the setup for the wood.

## Results and Discussion

As the tests were conducted, it was immediately noticed that the sheet piling did not stay level during the loading for the “Plate” set of experiments that used the steel plates as constraints. Even though the simple supports that the sheet pile section was supported on were determined to be level using the carpenter’s level, the sheet pile with the steel constraint plates was twisted while sitting on the supports even before being loaded due to the nonsymmetrical weight distribution of the steel plates. As load was introduced, the degree of the twisting increased as the bubble of the carpenter’s level was seen to move significantly during the test until loading advanced to a sufficient level. The magnitude of twisting of the sheet pile before and during loading increased as the test span increased. This observation from the examination of the carpenter’s level was confirmed through the use of two dial gages used to directly measure the displacement of the underside of the pile section at the flange at the mid-point of the span. Each dial gage was located 2 inches from the edge of the bottom flange surface. At zero load, both dial gages began at zero, but their readings diverged until a load of about 500 lb was reached. At 300 lb, the dial gage readings differed by about 0.060”. However, as the load continued to increase, the dial gage readings did not continue to diverge. The use of the dial gages also demonstrated that the bottom flange surface of the sheet pile did not displace the same amount as the amount of displacement recorded using the actuator LVDT for the entire sheet pile section. For example, during one of the “Plate” experiments at a 15 ft span, data recorded at 302 lb indicated .5649 inches of LVDT displacement, 0.466 inches of displacement at one side of the bottom flange surface, and 0.399 inches of displacement at the other side of the flange surface (all recorded at mid-span). The different readings between the LVDT and the dial gages, based on where the displacement measured was taken, are due to a combination of the sheet pile spreading and probably more so to the pile twisting. For the “Strap” and “Restrap” tests, the sheet pile section was initially level, and remained level throughout the tests. Therefore, twisting of the sheet pile did not contribute to the LVDT measured displacement for the “Strap” and “Restrap” tests, but a small amount of the LVDT measured displacement did occur as the web sections of the beam spread apart for the “Strap” and “Restrap” tests. For example, during the StrapBlock-Cut3-5 experiment, a total amount of 0.25 inches of horizontally measured spreading of the web sections was recorded using a tape measure during the test, and there would have been some actuator displacement that occurred in conjunction with this. The “Plate” experiments were more rigidly constrained from spreading, so even less spreading of the web would have been experienced for the “Plate” experiments. This data demonstrates that slightly higher EI values would be calculated if displacement gages on the lower flange were used instead of LVDT displacement readings. For example, the calculated EI for one of the “Plate” experiments at a 15 ft span is 71.6E+06 lb·in$^2$ if the LVDT displacement data is used and is 80.6E+06 lb·in$^2$ if displacement gage data is used.

The “Plate” set of experiments was seen to be much less repeatable for the same span in comparison to the repeatability seen for the “Strap” and “Restrap” sets of experiments. A comparison of Figures 3 and 8 illustrates the differences seen in the repeatability of these sets of tests. As seen in Figure 3, the repeatability within the “Strap” and “Restrap” sets of experiments was excellent, and even after removing the first set of straps and installing a second set of straps for the “Restrap” set of experiments, the data obtained was very similar. This demonstrates that even though the straps are installed by hand and must be installed separately on each sheet pile tested, this method can be used to generate reproducible data. The benefit of not having to machine a complicated shape in numerous steel plates for each different sheet pile section tested is also a significant benefit of the use of the strap constraint method.

A comparison of the apparent pile rigidity (EI) determined from each of the sets of initial tests is shown in Figure 9 for each of the sets of tests. In this figure, the the rigidity of the pile as determined by the E times I product is graphed vs. the span of the flexural test. Each EI value was determined using the equation for a simply supported beam with a concentrated center load

$$\delta = \frac{PL^3}{48EI} \qquad (1)$$

where:
$\delta$ = deflection at mid-span,
P = load applied at mid-span,
L = support span,
E = section flexural modulus, and
I = moment of inertia.

The EI data point shown for each test in Figure 9 is an average of the values calculated for each test between 500 and 900 lbs of load. There was some variation in the calculated values over the load range for all of the samples, but after sufficient load had been applied for the slack to be removed from the sample and test setup, the calculated EI values remained similar during the test. Slightly more variation was seen in these values at lower loads for the "Plate" and "Woodstrap" sets of experiments as the loading apparatus for those methods settled and compacted to begin uniformly loading the samples. Examples of the calculated EI stiffness values for the Restrap9 experiment are shown in Table 1.

As seen in Figure 9, the EI product varied with span for each set of tests. As previously noted, there was very good agreement for the "Strap" and the "Restrap" sets of data. The trend of increasing EI with increasing span ratio suggests that the flexural properties were influenced by shear, with the shear having less of an effect as the span increased. For the "Strap" and "Restrap" sets, it appears that the 14 ft and 15 ft spans used in these tests for this sheet pile section geometry are approaching the necessary value to minimize the influence of shear on the measured EI values.

For standard ASTM D790-03 a minimum span-to-depth ratio of 16:1 is recommended with larger ratios recommended if shear failure occurs in the sample. The spans of 11.5 ft. to 15 ft. represent span-to-depth ratios from 23:1 to 30:1 for this sheet pile section. However, Bank has suggested that instead of span-to-depth ratio, the ratio of span-to-radius of gyration is the more appropriate ratio to examine for thin-walled composite sections [3]. The spans of 11.5 ft. to 15 ft. represent span-to-radius of gyration ratios from 70:1 to 91:1 for this sheet pile section. As tests on additional sheet pile profiles are conducted, the necessary ratios to minimize the effects of shear on the apparent section modulus values will be determined for other profiles.

For all spans examined, it is seen that the EI values for the "Plate" set of data are lower than the EI values recorded for both the "Strap" and "Restrap" sets of experiments for a given span, with the EI values recorded for the "Woodstrap" set of experiments being in between these. The fact that the sheet pile section was seen to deform during the test as evidenced by the movement of the level bubble during the "Plate" set of experiments suggests that only bending of sheet pile did not occur for this set of tests and the EI values that were recorded were not truly representative of the section rigidity for the sheet pile. On the other hand, the observation that the sheet pile did not distort during the testing for the "Strap" and "Restrap" tests suggests that this method could be more representative of the section modulus of the sheet pile. Slightly more distortion was seen from examination of the level for the "Woodstrap" tests than for the "Strap" and "Restrap" sets of experiments. Also, it is suspected that the loading methods using the sand-filled cavity, the wood section with the layer of sand below the wood to help uniformly contact the sheet pile section, and the plywood all under the 8" x 24" x 1" steel loading plate for the "Plate", "Woodstrap", and "Strap" and "Restrap" sets of experiments, respectively, could have contributed to this trend seen in the EI data. The "Plate" set of experiments with the sand had the load distributed over most of the sheet pile section surface at the top, sides and lower surfaces. The "WoodStrap" set of experiments had the load distributed on the lower surface with the layer of sand below the wood section with some contact between the wood section and the sides of the sheet pile. The "Strap" and "Restrap" sets of experiments only had the load distributed over the top surface of the sheet pile where it contacted the loading plate.

Figure 10 shows the results of the various "Strap-BlockCut#" experiments. As can be seen, at the loading levels used for this testing there appears to be little effect on the number of straps used to constrain the sheet pile as long as long as the outside strap and the inside strap near the loading nose are in place. The "Strap" and "Restrap" EI values are seen to be slightly higher when compared with the "StrapBlock" and "StrapBlockCut#" data implying that the strap tension may be an influence on the apparent section modulus, but is not a major factor at least at the low loads used in these sets of experiments. At higher loads required to break the sheet piling, the effect of the strap tension and the number of straps required to maintain the pile shape may be much more important. Similar to Figure 9, Figure 10 also shows the effect of shear on the shorter spans; only at higher span lengths are the data approaching the necessary value to minimize the influence of shear on the measured EI values.

For comparison, the sheet pile with the steel plate constraints was also tested in the inverse orientation; this procedure eliminated the need to use sand to fill the cross-section to allow the load to be distributed across the flange. When testing the sheet pile in the inverse orientation, the load was distributed over the center flange section as it was in contact with the loading nose. Less initial twisting of the sheet pile as it sat on the supports was seen when this orientation was used. Since less initial twisting occurred and the load was more easily applied over the center flange surface using this configuration, less LVDT deflection occurred due to twisting; the resulting load vs. deflection curves for each orientation are seen in Figure 11. The average EI for Plate 1 was 70.2 lb·in$^2$, and the average EI for the same sample tested using the inverted orientation was 75.8 lb·in$^2$.

For all of the test techniques examined, it was evident that additional displacement occurred at lower loads as events such as twisting and web spreading occurred as discussed earlier. Examination of Table 1 gives an example of this, with lower EI values being seen for the initial loading levels. For all average EI data presented in this paper, average EI values were calculated from the 500 – 900 lb. load range. Another approach that could be used to account for the initial displacement that is not directly attributable to bending of the sheet pile is to use delta load and delta displacement values to calculate EI data. As seen in Table 1, EI calculated using data points from the 500 – 900 lb range gives an average value of 79.6 lb·in$^2$. If the delta load and delta displacement for each data point in this range is used to calculate EI, the average value is 81.0 lb·in$^2$.

## Summary and Recommendations

The test method using flexible plastic pallet straps to constrain the sheet pile during the flex tests shows promise as a test method for determining the EI stiffness of sheet piling. Based on visual examination of a carpenter's level placed on top of the sheet pile during testing, little to no twisting of the sheet pile was evident at the load levels examined for these tests. Significant amounts of twisting were seen during the tests conducted using the steel support plates.

The use of the flexible plastic pallet straps met a number of the desirable characteristics for a flexural test method for sheet piling. The plastic straps did not damage the sample being tested, were easy to set up for different profile geometries, can uniformly constrain the sample, did not cause local damage to the sample, and produced repeatable data. Also, the spacing of the straps and the strap tension appear to not be major factors at the low loads used for the present tests. Ideally, the constraint method used would not result in damage to the sample being tested, would be easy to set up for different profile geometries, would uniformly constrain the sample, would not cause local damage during loading, and would be repeatable.

Based on the results seen in this preliminary investigation, additional tests using the strap method are recommended and will be conducted for this project. Additional tests will be conducted to quantify the amount of distortion that occurs during flexural testing when the constraint straps are used. Also, the load level for which the straps can successfully act as constraints will be evaluated to determine if this method can be successfully used for testing of sheet piling to failure. It is likely that heavier duty straps will be required for tests taken to failure loads. To constrain the sheet piling at the higher failure loads, support for the inside surfaces of the sheet pile may be necessary at the location of the straps as well. If it is determined that support inside the sheet pile section is required, the use of supports made of various materials such as such as wood or rigid foam will be evaluated, and the optimal method of load introduction will be investigated further. Additional tests will also be performed to evaluate these methods for other sheet piling profile shapes.

## References

1. Lampo, Richard, et al, "Development and Demonstration of FRP Composite Fender, Loadbearing, and Sheet Piling Systems," US Army Corps of Engineers Construction Engineering Research Laboratories (USACERL) Technical Report 98/123, September, 1998.
2. http://www.astm.org, accessed May 2007.
3. Bank, Lawrence C., "Flexural and Shear Moduli of Full-Section Fiber Reinforced Plastic (FRP) Pultruded Beams," Journal of Testing and Evaluation, Vol. 17, No. 1, Jan., 1989, pp. 40-45.
4. Mottram, J. T., "Evaluation of Design Analysis for Pultruded Fibre-Reinforced Polymeric Box Beams," The Structural Engineer, Vol. 69, No. 11, June, 1991, pp. 211-220.

5. Zureick, A. and L. F. Kahn, "Tests on Deep I-Shape Pultruded Beams," Journal of Reinforced Plastics and Composites, Vol. 14, April, 1995, pp. 378-389.
6. Sims, G. D., A. F. Johnson, and R. D. Hill, "Mechanical and Structural Properties of a GRP Pultruded Section," Composite Structures, Vol. 8, 1987, pp. 173-187.
7. Giroux, Cynthia and Yixin Shao, "Flexural and Shear Rigidity of Composite Sheet Piles," Journal of Composites for Construction, Vol. 7, No. 4, November, 2003, pp. 348-355.
8. Shao, Yixin, "Characterization of a Pultruded FRP Sheet Pile for Waterfront Retaining Structures," Journal of Composites for Construction, Vol. 18, No. 5, October, 2006, pp. 626-633.

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**Biography**

Ellen Lackey: Dr. Lackey, CCT-I, is an associate professor in the Mechanical Engineering Department at the University of Mississippi. Her research areas focus on the manufacturing and testing of polymeric composites.

James Vaughan: Dr. Vaughan is a Barnard professor of Mechanical Engineering at the University of Mississippi. He is the Director of the Composite Materials Research Group at the University.

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Jeremy Mostoller: Mr. Mostoller is a Product Design Engineer with Creative Pultrusions, Inc. He has spent much of his career working in the field of structural design using composite materials.

Table 1. Calculated EI Stiffness Data for Restrap9

| Load (lb) | Actuator Deflection (in) | Stiffness (EI) ($lb \cdot in^2$) |
|---|---|---|
| | | |
| 100 | 0.1751 | 69.7E+06 |
| 200 | 0.3267 | 74.5E+06 |
| 300 | 0.4750 | 76.8E+06 |
| 400 | 0.6217 | 78.2E+06 |
| 500 | 0.7684 | 79.1E+06 |
| 600 | 0.9184 | 79.5E+06 |
| 700 | 1.0667 | 79.7E+06 |
| 800 | 1.2184 | 79.8E+06 |
| 900 | 1.3718 | 79.7E+06 |
| average (500-900 lb) | | 79.6E+06 |

Figure 1. Buckling of unsupported sheet pile during testing at very low load levels.

Figure 2. Geometry of sheet pile section tested for this project.

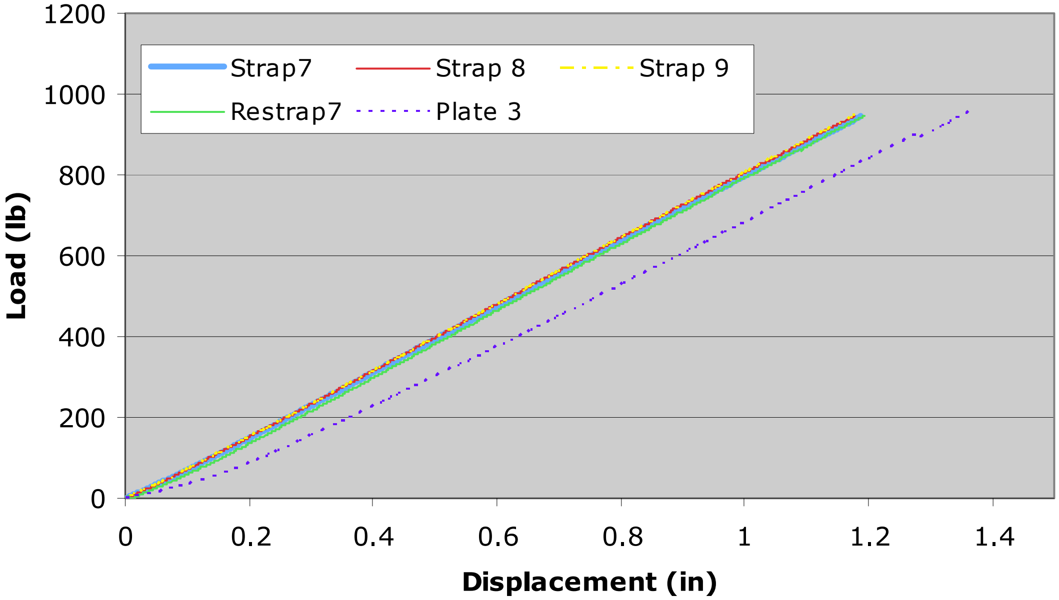

Figure 3. Results of replicate tests for Strap7, Strap8, Strap9, and Restrap7, and Plate 3 tests all conducted at 14 foot test span.

Figure 4. Wood support fit into the inside opening of the sheet piling.

Figure 5. Steel plates showing cutout geometry.

Figure 6. Flexural test setup showing the spacing of steel plates down the length of the sheet piling.

Figure 7. Steel constraint plates forming cavity filled with sand for loading of the sheet piling.

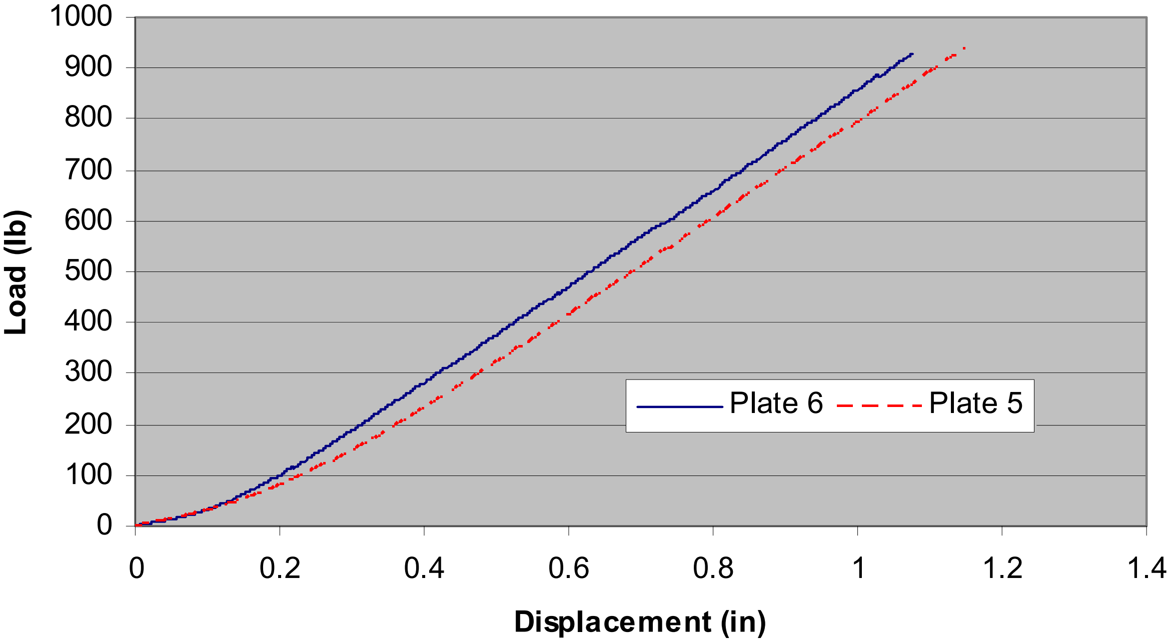

Figure 8. Replicate tests conducted at 13 foot span using steel constraint plates.

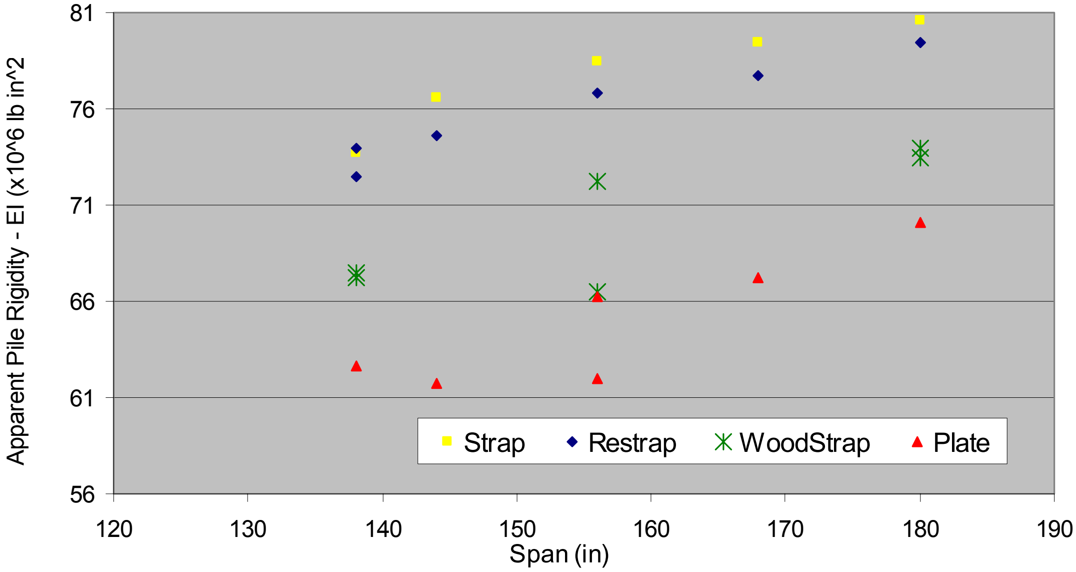

Figure 9. Effect of span length on sheet pile rigidity determined from three-point flexural testing based on different methods of constraining and loading the sheet piling.

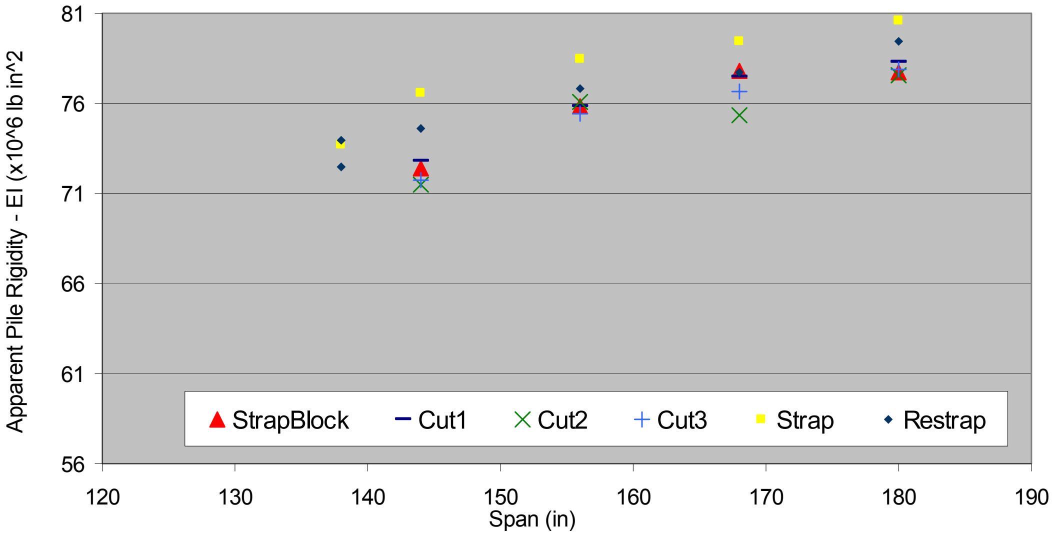

Figure 10. Effect of span length on sheet pile rigidity based on number of straps used and strap tension.

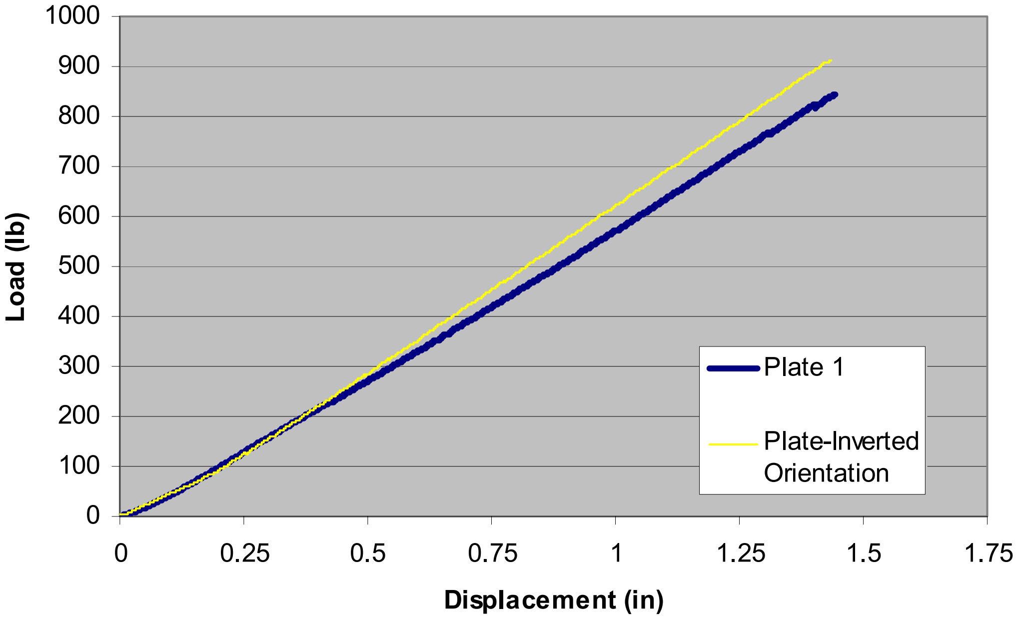

Figure 11. Comparison of load vs. displacement data for “Plate” experiments loaded with center flange section on supports (Plate 1) and the same sheet pile tested in an inverted orientation with the center flange section against the loading nose. Both tests were conducted at using a 15 ft support span.