DETERMINATION OF EI FOR PULTRUDED GFRP SHEET PILE PANELS

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Abstract

The flexural rigidity, EI, plays an especially important role in fiber reinforced polymer composite sheet pile wall design. Determination of EI is usually affected by the presence of the shear either due to the short testing span or to the low shear modulus of composites. To reduce or eliminate the effect of shear on the determination of flexural rigidity of composite sheet pile panels, this paper is to propose a test method that is based on Bank's multi-span approach and Timoshenko's beam theory. Tests were performed using three-point and four-point bending set-ups, with single composite sheet pile panel at six different spans, and with connected two panels at eleven spans. The results showed that six EIs determined independently from different set-ups, at different deflection points along the beam and with different cross sections gave values that differed from each other by less than 3%. The EI so determined was a constant independent from the test span, the test set-up, the location of the deflection point on the beam, or the number of data points used in linear regression. Apparent EIs calculated from single span tests were strongly span-dependent and approached asymptotically to the value determined by multi-span approach. It was likely that the multi-span approach yielded the highest possible flexural rigidity that could be measured. The shear effect was therefore eliminated.

Introduction

The pultruded fibreglass reinforced polyester composite sheet pile wall is a unique and one of its kind waterfront structure. The corrosion resistance and high strength-to-weight ratio of composites are the primary characteristics supporting this choice of material. The use of composites also features low maintenance, reduced life-cycle costs, dimensional stability, and near-zero environmental toxicity.

Composite sheet piling products have been currently used to a limited degree, or experimentally for light retaining structures along the waterfront and the coastline. Because of the lack of the field application history, the height of composite sheet piling is presently limited to 2 - 5 meters. Experimental projects included renovation of decayed timber walls as well as construction of new retaining walls. Standard procedure of installation is followed without any special equipment required.

The important parameter in sheet pile wall design is the flexural rigidity, EI, especially for FRP composite sheet pile wall. The wooden plank sheet pilings are about 50 mm × 300 mm solid in cross section. For precast concrete sheet piles, the cross sections range from 500 to 800 mm wide and 150 to 250 mm thick. Steel sheet piles in the United States and Canada, have thickness about 10-13 mm. Sheet pile sections may be Z, deep arch, low arch, or straight web sections. Compared to the traditional pilings, the composite sheet panels exhibit relatively low flexural rigidity owing to their thin walled structure (3-5mm thick) and low Young's modulus of panel members (E = 30-40 GPa). To help guide the proper use of composite piling products, US Army Corps of Engineers had set a number of specifications to classify products of different duties (Lampo, et al. 1998). The target flexural rigidities, EI, for different grades were proposed in a demonstration project for pultruded composite sheet pilings:

- Light-duty: $5x10^3$-$1x10^4$ to $1x10^4$-$5x10^4$ kip-sq in/ft
- Medium-duty: $5x10^4$-$1x10^5$ to $1x10^5$-$5x10^5$ kip-sq in/ft
- Heavy-duty: $5x10^5$-$1x10^6$ to $1x10^6$-$5.5x10^6$ kip-sq in/ft

To check with the specifications for a given product, it is essential to properly characterize the EI of the product. Determination of EI is usually affected by the presence of the shear. To avoid shear effect on the EI, ASTM D-790 recommended the span to depth ratio of the beam tests be at least 16:1. For the sheet pile walls made of traditional materials, the deflections due to shear might be negligible if the span is large enough. However, for composite materials, in addition to short span effect, the low shear modulus (*G*) could also cause the shear deflection to be significant.

This paper is to report an experimental study on determination of flexural rigidity of the pultruded composite sheet pile panels with reduced or eliminated shear effect. Bank's approach was adopted in three-point and four-point bending tests with various spans. Bank (1989) developed a method to simultaneously determine the section Young's modulus and the section shear modulus by using Timoshenko's deflection equation. The approach was modified in this paper to directly determine the EI, instead of E alone. Results from the three-point bending tests were compared with that from four-point bending tests to check the consistency, so were the results from single panel tests compared with connected double panel tests. The dependence of the flexural rigidity on the test conditions was also discussed.

Deflection Equation

Equation (1) gives the general form of Timoshenko's beam deflection theory. Because Timoshenko's theory uses superposition of the bending and shear deflections, it is limited to the linear elastic range of the material.

$$\delta = \frac{C_1 P L^3}{(EI)} + \frac{C_2 P L}{(kAG)} \tag{1}$$

Here, the deflection, δ, depends on the applied load, P, the span length, L, the flexural rigidity, EI, and the shear rigidity, kAG. The constants, C_1 and C_2, depend on the load case and on the particular location along the span length that the deflection is desired. Values for C_1 and C_2 are given in Table 1 for the cases of three-point bending and four-point bending at one-third span. Note that the flexural rigidity is defined as the product of the section flexural modulus, E_s, and the second moment of area, I, and the shear rigidity as the product of the factored area, kA, and the section shear modulus, G_s. The factor, k, is the shear coefficient for composite beams in flexure.

Table 1: Constants used in Timoshenko's equation

	Centre-point deflection ($\delta_{x=L/2}$)		Quarter-point deflection ($\delta_{x=L/4}$)	
	C_1	C_2	C_1	C_2
3-point bending	$\frac{1}{48}$	$\frac{1}{4}$	$\frac{11}{768}$	$\frac{1}{8}$
4-point bending	$\frac{23}{1296}$	$\frac{1}{6}$	$\frac{29}{2304}$	$\frac{1}{8}$

Equation (1) can be rearranged into Equation (2) which is in the form of a straight line with $\frac{\delta}{PL}$ as the dependent variable and L^2 as the independent variable. Knowing the slope of the load-deflection curve, $\frac{P}{\delta}$, and the span, L, of each beam tested, this straight line can be plotted. The slope and intercept of the line are inversely proportional to the flexural rigidity, EI, and the shear rigidity, kAG, respectively. Theoretically, Equation 2 can be used to simultaneously determine the EI and kAG. This paper will only discuss the possibility of obtaining EI with reduced or eliminated shear effect by conducting multi-span tests with minimum number of tests.

$$\frac{\delta}{PL} = \frac{C_1}{EI} L^2 + \frac{C_2}{kAG} \tag{2}$$

Experimental Program

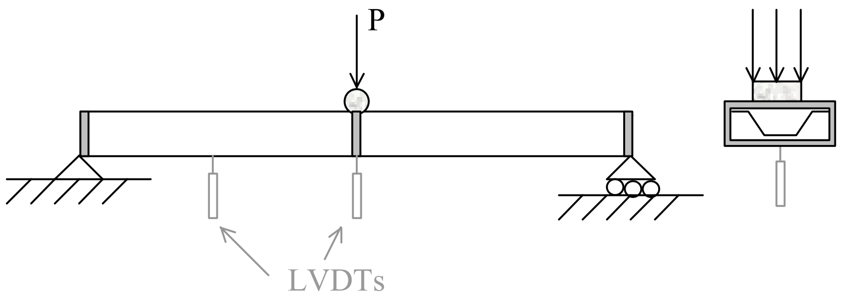
Single Panel Tests

The composite sheet piles used in this study was designed and manufactured by Pultronex Corporation (Nisku, Alberta). The corrugated profile of a single panel has a symmetric double Z cross section. The panels are approximately 12.7cm deep, 42.5cm wide, and have a thickness varying from 0.32cm to 0.47cm. The panels interlock with each other through the pin and eye connections on both ends to form a continuous wall (Figures 1 and 2). The pultruded profile consists of layers of E-glass rovings and mats in a polyester matrix.

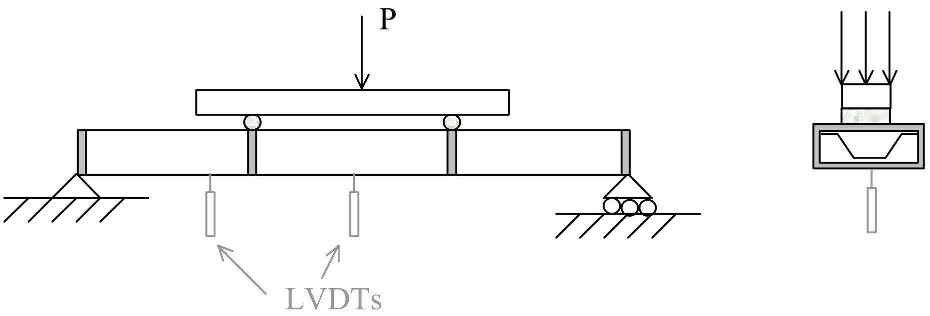
Tests were performed first with single panel in three and four-point bending tests (Figure 1) on spans of length 0.91, 1.52, 2.13, 3.05, 4.57, and 6.10 meters, (3, 5, 7, 10, 15, and 20 ft) within the linear proportional limit of the material. Tests on each span were repeated a minimum of three times. The beams were loaded using an MTS testing machine with an average loading rate of 0.03mm/s. The deflections at midpoint as well as at one quarter point along the span were measured using two linear variable differential transducers (LVDTs) with ranges of 10cm. The data were recorded using a Measurements Group System 5000 data acquisition system using the Strain Smart software. For four-point bending tests, the load points were equally spaced at one-third span. Rigid steel frames of square tubes (25 mm x 25 mm x 2 mm thick) were constructed and positioned at the supporting and at the loading points of the beam in order to distribute the applied load and provide lateral confinement on the open section of the sheet pile (Figure 1).

Connected Double Panel Tests

To examine if the connected panels had different flexural rigidity, tests of connected double panels were also performed using the four point bending setup at equal space with eleven spans, 1.5, 1.8, 2.1, 2.4, 3.1, 3.7, 4.3, 4.9, 5.5, 6.1, and 6.7 meters (5, 6, 7, 8, 10, 12, 14, 16, 18, 20, and 21.8 ft), and within the linear proportional limit. Each span test was repeated a minimum of three times. A pin and an eye were inserted at both ends of the connected double panels to simulate the connected wall as shown in Figure 2. Steel straps of size 2.5 cm (1 inch) wide and 1 mm thick were used to tie around the cross section, in order to confine the panels and to limit the lateral displacement. The use of flexible steel strapping at a uniform spacing of 61 cm (2 feet) was to provide a uniform restrain and prevent the panels from being stiffened by rigid heavy steel frame.



(a) Three-point bending set-up for single panel tests



(b) Four-point bending set-up for both single and double panel tests

Figure 1: Flexural test set-ups

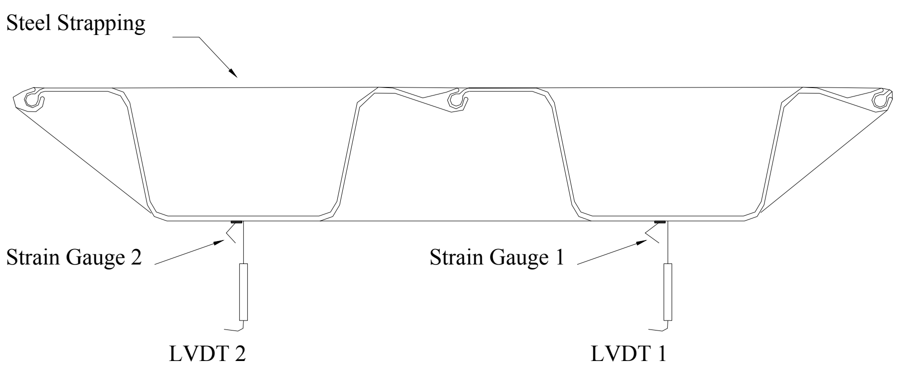


Figure 2: Cross section of connected double panels

Results

Single Panel Tests

Typical curves within the linear proportional limit for the load versus midpoint displacement for the six spans are given in Figure 3 for the four-point bending tests. Linear fits using the method of least squares were performed on the load-deflection curves in Figure 3. Four sets data of load versus deflection were recorded in different set-ups (3-point and 4-point) and at different locations along the beam (midpoint and quarter point). The linear fit provided values for the slope, $\frac{P}{\delta}$, for each span, L, which allowed $\frac{\delta}{PL}$ and L^2 to be calculated for use in the rearranged Timoshenko beam theory equation (Equation 2).

For the deflection measured at the midpoint, the results of plotting this data with $\frac{\delta}{PL}$ as the dependent and L^2 as the independent variables are plotted in Figure 4 for the four-point bending tests for all six span tests. For each span, at least three independent tests were performed and thus three sets of data on the $\frac{\delta}{PL}$ versus L^2 were plotted in the same graph. As is seen, good repetition was achieved. Similar data process was carried out for three-point bending tests.

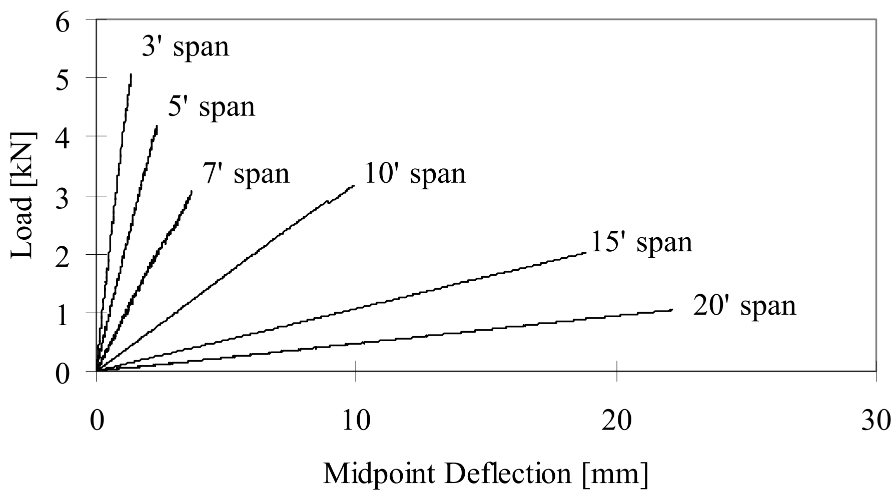


Figure 3: Typical load-deflection curves at the midpoint
for four-point bending linear tests (single panel, 1' = 0.3048m)

Linear fit was then carried out again using the least square method to determine the equation of the line in Figure 4. Based on Equation 2, the slope of the line was proportional to C_1/EI and could be used to calculate the flexural rigidity for the case. Tests and data process were repeated for other three cases and results are presented in Table 2.

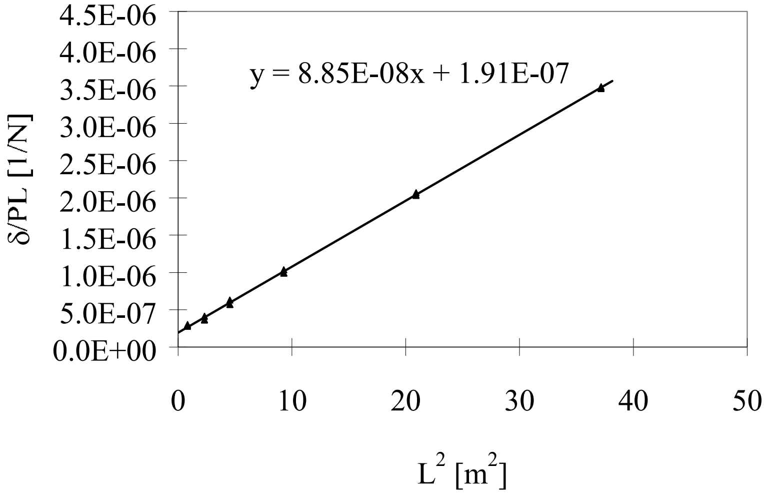


Fig. 4: Straight line used to determine the flexural rigidity
from four-point bending based on the midpoint deflection (single panel)

Connected Double Panel Tests

Similar procedure was followed for connected double panel tests. The typical load – deflection curves for eleven span tests are shown in Figure 5 for deflection measured from LVDT 1 at midpoint. Slope of each linear test was determined by averaging readings of LVDT1 and LVDT2 at midpoint. δ/PL versus L^2 was then plotted in Figure 6 for eleven different spans. The linear fit of all data points was performed to find equation of the straight line. Based on equation 2, the slope could be used to calculate the flexural rigidity of the connected panels. The same procedure was followed to obtain the EI from the quarter point load- deflection data. The final results were divided by two to obtain the rigidity for single panel and also presented in Table 2 for comparison.

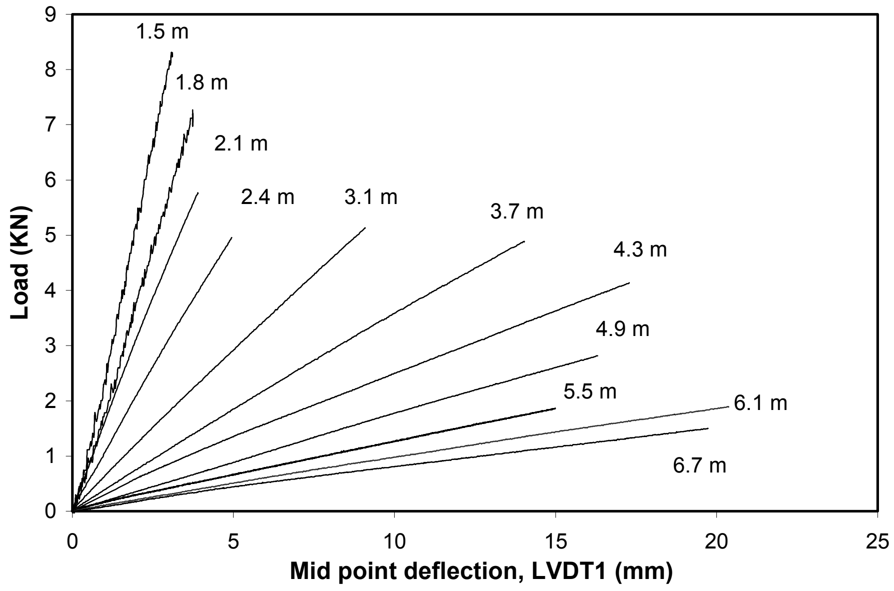


Figure 5: Typical load – deflection curves at the midpoint
for four-point bending linear tests (LVDT 1, connected double panels)

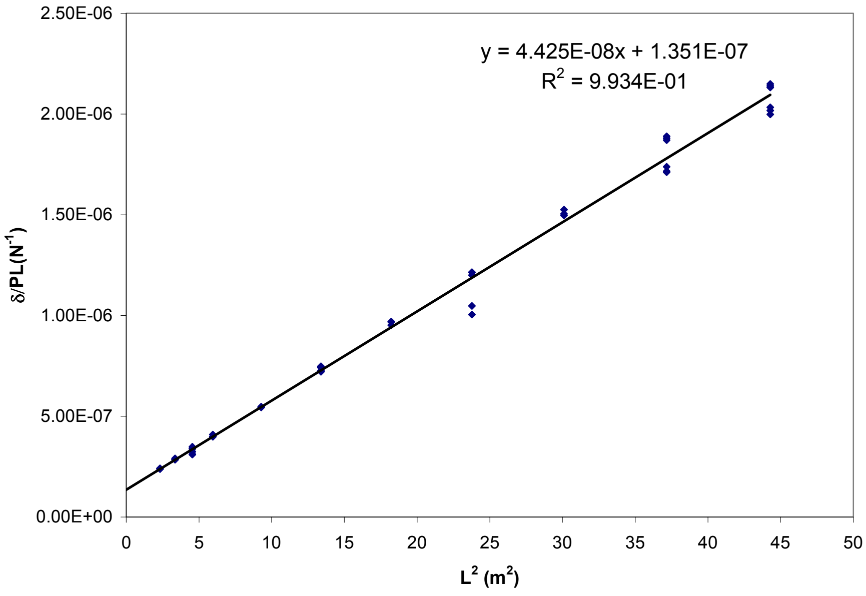


Fig. 6: Straight line used to determine the flexural rigidity
from four-point bending based on the midpoint deflection (connected double panels)

The values obtained for the flexural rigidity agreed with each other for both three and four-point bending tests, both midpoint and quarter-point data, and both single and double panels. The average was calculated with a standard deviation of 2.9%. These self-checks are strongly supportive of the proposed experimental method.

Table 2: Flexural rigidity of single panel determined by multi-span test method

	Midpoint deflection ($\delta_{x=L/2}$)	Quarter-point deflection ($\delta_{x=L/4}$)	Difference [%]
EI (single panel)			
3-point bending EI [kNm^2]	212	216	1.8%
4-point bending EI [kNm^2]	201	200	0.5%
EI (two connected panels)/2			
4-point bending EI [kNm^2]	201	206	2.4%
Average EI [kNm^2]	206±6		2.9%

Apparent Flexural Rigidity

The apparent flexural rigidity, $(EI)_a$, is defined as the resistance of a beam to deflection due to only bending, neglecting shear deflections. The slopes of the load-deflection curves were used to determine the apparent flexural rigidity based on the first term of Timoshenko's equation. They are presented in Figure 7 as $(EI)_a$ vs span to depth ratio. Obviously, the apparent flexural rigidity varied with the span to depth ratio, indicating that shear did have effect on flexural rigidity obtained from single span tests. In both curves (mid and quarter points in Figure 7), the apparent flexural rigidity increased with the increase of span length. This suggested that a lager deflection contribution from the shear was present with shorter spans compared to longer ones. The apparent flexural rigidity asymptotically approached to 400KNm^2, the EI determined by two-term Timoshenko's Equation. It was likely that EI defined by Equation 2 was the largest possible rigidity that could be experimentally measured. Since Equation 2 separates the bending and shear contributions to the total deflection, the effect of shear on the EI is actually eliminated. ASTM D 790 suggests a span to depth ratio of 16/1 or higher be used in beam tests to avoid shear effect. At this suggested ratio, the apparent flexural rigidity of the sheet pile panel counted to only 44% of the maximum possible value.

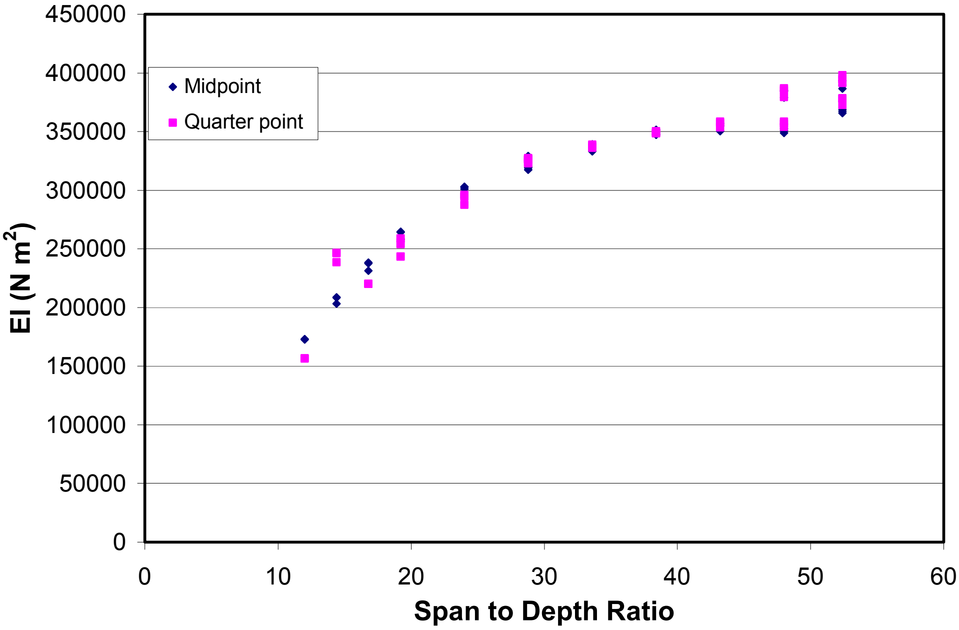


Fig. 7: Apparent flexural rigidities versus span-to-depth ratio (connected panels)

Sensitivity of EI to Data Process

It was noticed during data processing that flexural rigidity (EI) was insensitive to the span and the number of data points used in the linear fit. The flexural rigidity of connected double panels is the result of tests of 11 spans, from 1.5 m to 6.7 m, the last two data points shown in Figure 8 with all spans. Effort was made to examine if only a few small span tests would be enough to generate the comparable EI. The results are shown in Figure 8, in which EI is plotted versus the largest span included in linear fit. For instance, the first set of EI (from both midpoint and quarter points) was computed by linearly fitting test data of three smallest spans: 1.5, 1.8, and 2.1 meters. The largest span included in the linear fit was 2.1 m. Thus, EI was plotted against 2.1m. Subsequently, the rest used test data of four spans with the largest 2.4m, of five spans with the largest 2.7m, and so on until the last set of all spans with the largest 6.7m. It was interesting to notice that variation of EI with test span and numbers of data in linear fit was not significant. In the other words, by using multi-span test method, EI could be determined consistently even with only three small-span tests.

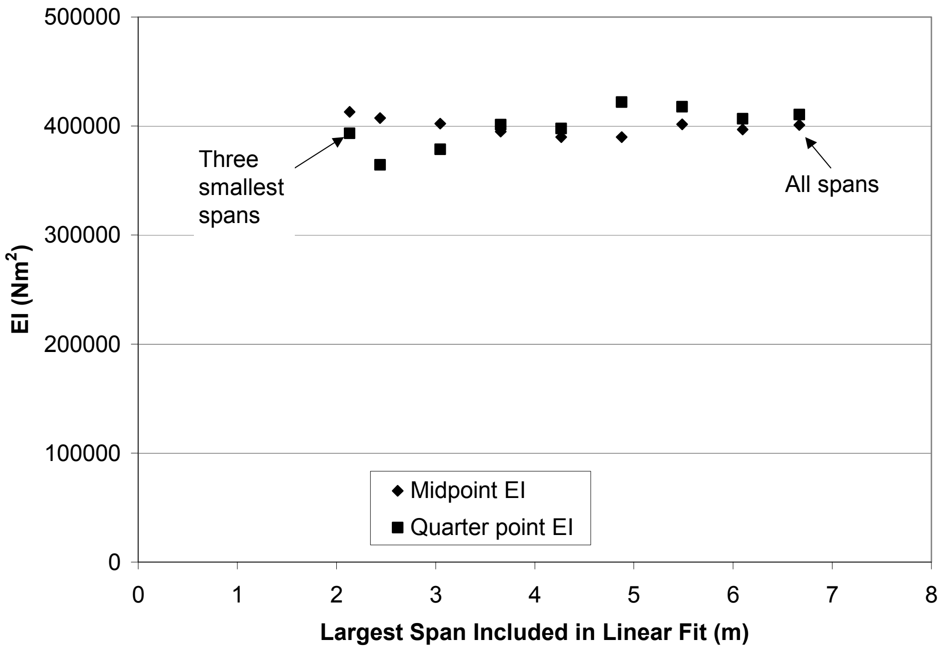


Figure 8: Sensitivity of EI on largest span included in linear fit (connected panels)

Discussion and Conclusions

The flexural rigidities were determined for the fiberglass composite sheet pile panels using a modified Bank's multi-span approach. Values were found by performing both three and four-point bending tests, by taking deflection measurements at the midpoint and at the quarter-points of the span, as well as by using single panel and connected double panels. Six flexural rigidity results from independent tests agreed well with a standard deviation of 2.9%. The frames used for confinement did not affect the results. It seemed proper to group EI together as section parameter for composite sheet pile wall design. The flexural rigidity determined by the proposed multi-span method was quite different from that measured by the traditional single span method unless the span to depth ratio was over 60. The multi-span method gave the largest possible EI value with eliminated shear effect. EI so determined was a section constant independent from span length and numbers of tests, as long as minimum of three tests of different spans were performed. The average EI of the single panel was about 206 kNm^2. In US customary units, it was corresponding to 5.47×10^4 kip-sq in/ft and the product was graded in the low end of medium duty according to specifications set by US Army Corps of Engineers. The same product however could be classified as light duty if only single span tests were performed. Therefore, standardization of the test method for composite sheet pile panels is necessary to make fair comparison for different products. The multi-span test method is strongly recommended in this regard.

Acknowledgment

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