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Hybrid Pultruded Plank with a Concrete Compression Flange for Pedestrian Bridges

by

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Abstract

The goal of this study was to determine the feasibility of using a commercially produced 2 inch deep fiber-reinforced polymer (FRP) plank with a 0.75 – 1.0 inch cast-in-place concrete or cement board compression flange as a replacement for conventional timber 3” x 12” decking bridge deck for pedestrian or light-weight vehicle bridges (such as snowmobiles or snow removal tractors.) A number of different specimens were fabricated and tested in three point bending experiments. Bonded, cast-in-place and mechanically fastened concrete and cement board compression flanges were investigated. The stiffness and strength of the hybrid deck panels were compared with that of a conventional 3” x 12” timber deck panel. Failures were due to debonding between the pultruded plank and the concrete or cement-board compression flange or due to crushing of the compression flange. Preliminary analysis reveals that the hybrid plank can lead to support spacing of about 6% more than allowed with 3” x 12” timber planks based on a deflection limits. Flexural strength was similar to the timber beams. The beams with the cement-board compression flanges were about 75% the strength of the timber beams per foot width while the beams with the concrete compression flanges were about 55% the strength of the timber beams per foot width, for the specific geometries of the specimens tested in this research. However, since the deflection controls the design of these panels a safety factor larger than 2.5 can still be maintained for these deck panels assuming light-weight vehicles up to 2 tons.

Introduction

Fiber-reinforced polymers (FRP) are becoming popular for many bridge projects today due to their long life span and low cost of installation (Bank, 2006). FRP has the ability to be more durable than steel and timber since it does corrode like steel or decay like timber. Pedestrian bridges present a potential application area where FRP and concrete hybrid composite structural elements can be used. Today, timber is the main material used in pedestrian bridge decks. Although timber is relatively inexpensive, construction time is long because each individual 3” x 8” piece of decking needs to be placed and bolted down. In addition, timber decays over time causing problems with bridge deck durability. On the other hand, FRP does not deteriorate, which allows it to have a life span much longer than timber—75 years or more.

Objectives of the Research

The main objective of this research is to combine two different materials – one which performs well in compression and one which performs well in tension – to create a hybrid panel optimized for performance in bending. One advantage hypothesized with this hybrid panel is that it will be able to reduce the number of support beams or trusses in a bridge. The research investigated if the hybrid panel could achieve sufficient stiffness in order to increase the spacing between support beams allowing possible reduction of beams. In addition, the research investigated the effectiveness of different methods of bonding the two materials to create the hybrid panel. Previous research has indicated the main difficulty with hybrid materials involving FRP is achieving full composite action between the FRP and other material (Bank et al, 2006). Often failure will occur at the bond interface rather than in the materials themselves. Epoxy, mechanical fasteners, and concrete bonding with epoxy are the three methods of bond attempted in this study. Foam was considered to be used to aid in preventing shear failure in the webs of the FRP plank, but this was found unnecessary.

Fabrication of Specimens

Five different hybrid specimens were fabricated for testing. Each specimen measured 72” x 16” x 2.75” with differences in materials and shear transfer mechanisms. Figures 1 and 2 display the design of the cement board specimen with mechanical fasteners as the shear transfer mechanism and the concrete specimen. In addition, Table 1 provides properties of each specimen and the labeling procedure.

Specimen 1 was composed of a commercially available FRP pultruded plank and a commercially available cement board material. The FRP pultruded plank has a base plate with integrated T-shaped ribs protruding from the base plate. Tensile tests have shown that the FRP pultruded plank has a longitudinal tensile strength of 69,800 psi and a longitudinal modulus of elasticity of 3.9×10^6 psi (Ringelstetter et al, 2006). The cement board specifications state that it has a compressive strength of 2,500 psi and a modulus of elasticity of 6.0×10^5 psi (USG, 2006). This specimen was created by placing epoxy on the top of the flanges of the FRP pultruded plank and also on the areas on the cement board where the flanges would be in contact. The cement board was then placed on the plank flanges and concrete blocks were placed on top of the cement board to hold the board in place until the epoxy cured.

Specimen 2 and Specimen 3 were also composed of cement board and the FRP pultruded plank. In these specimens, the shear connection between the two specimens was made using mechanical fasteners, specifically sheet metal or dry wall screws. In Specimen 2, the intent was to achieve failure in the mechanical fasteners rather than the two base materials. The mechanical fasteners used were 1 ¼ inch long #6 self-drilling sheet metal screws. The fasteners were placed along each of the four flanges spaced at 3 inches along the span. Along each flange the screws were alternated from one side of the web to the other in order to evenly distribute the shear forces throughout the flange. Specimen 3 was designed in order to ensure failure in the cement board. In this specimen, 1 ¼ inch #9 cement board screws with varying thread sizes were spaced at 1 inch to achieve sufficient shear transfer between the cement board and pultruded plank. This design may not be practical for use, but the goal of this test was to achieve failure in one of the hybrid materials, specifically crushing of the cement board in the compression flange. Again, the location of the fastener on the flange was alternated in order to ensure an even force transfer throughout the flange and web (Figure 3). For both specimens, pre-drilling was performed. This method may not be necessary, but it was found easier to complete fabrication with pre-drilling in this study. Without pre-drilling, the mechanical fastener would have trouble penetrating the FRP plank flange.

Specimen 4 and Specimen 5 were composed of normal weight concrete and the FRP pultruded plank. Each specimen was composed of a 1" concrete compression flange with the FRP pultruded plank embedded ¼" into the concrete (Figure 4). Concrete cylinder tests found that the concrete had a compressive strength of 4,300 psi. The specimen was fabricated by first creating formwork for the concrete. Concrete was mixed and poured into the formwork (Figure 5). The FRP pultruded plank was then pushed into the concrete and a vibrator was used to help drive the plank into the concrete. Stops were placed on the formwork in order to ensure the plank achieved the correct depth. The flanges of the FRP plank embedded in the concrete were coated with wet epoxy to aid in increasing the bond strength between the concrete and FRP. No other surface treatment (such as sanding or aggregate grit surface coating) was performed on the flanges of the pultruded plank.

As controls, it was also necessary to test a common timber section currently used in the pedestrian and light-weight vehicle decking along with the pultruded plank with both Ts up (Specimen 6) and Ts down (Specimen 7). The timber tested was a nominal 3 x 12 (2 ½" x 11 5/16" actual) Douglas Fir which was untreated (Specimen 8). The timber was select grade with no visible knots.

Experimental Set-up and Instrumentation

For ease of description, a labeling procedure as seen in Figure 6 has been used. The flanges are labeled sequentially from 1 to 4 going from the west edge of the specimen to the east.

The test set-up for the specimens is shown in Figure 7. The supports were steel rods placed in slotted steel plates which provided a simply-supported specimen allowing rotation at the ends. The center-to-center spacing of these rods was 66 inches.

Load and deflection at midspan were measured on every specimen. Strain gages were placed on the compression surface and tension surface of the all specimens except Specimen 1 and Specimen 8. The gages were offset 3" in the longitudinal direction from the midspan to avoid the load head and placed directly above and below web 2. Figure 8 shows the instrumentation set-up for the specimens.

Each specimen was tested in three-point bending. The tests were displacement controlled using a constant displacement of 0.1 inch/minute. A ½" thick steel plate and ¾" neoprene pad was placed between the load head and the specimen in order to prevent local crushing of the material below the load head.

Experimental Results

Experimental Emphasis

The important considerations from the tests were the load capacity and stiffness of the specimens. Since most pedestrian bridge deck spans are deflection controlled, the stiffness of the material was important to determine the effectiveness of the hybrid material in comparison to the timber and FRP plank alone. It was important to also consider any slip that occurred at the bond interface. The load and deflection data can be used to determine at what point slip occurs in any specimen. Fully composite action was desired, but for some of the specimens partially composite action was expected to be observed.

Normalization of Data

Before any data could be analyzed, it was necessary to normalize the data in order to have consistent comparisons. For instance, all the specimens, except the timber specimen, had a width dimension of 16 inches. The timber specimen had a width dimension of 11 5/16 inches. Because of this difference in dimension, it was decided to normalize the load data to per foot of width. This provided a standard for which the data could be compared. The raw data load-deflection plots for all specimens can be seen in Figure 9 and the normalized load-deflection plots can be seen in Figure 10. Table 2 displays the failure loads and deflections for each specimen.

Capacities and Failure Modes

Most failures for the specimens were seen at the interface between the cement board or concrete and FRP plank. Specimen 1 failed with a sudden debonding failure (Figure 11). The specimen reached a load of 5,180 lb and a deflection of 1.19 inches. This equates to a normalized load of 3,877 lb/ft width. Only the section of the specimen between the north support and load point failed in debonding; the remainder of the specimen stayed intact (Figure 12).

Specimen 2 was designed to fail at the interface between the cement board and the FRP plank as previously mentioned. Failure of this specimen began at a load of 3,500 lb. Failure of the mechanical fasteners could be heard as popping sounds occurred with the failure of each individual screw. As failure occurred, slip of the cement board from the FRP plank could be observed (Figure 13). A gradual failure occurred over the final 0.5 inch of deflection with popping sounds heard frequently. The test was finally stopped at a load of 3,820 lb when the largest load drop of about 100 lb was seen as the failure of the screws continued. This equates to a normalized load of 2,864 lb/ft width. At this point, the deflection had reached a maximum of 2.67 inches. The strain data in Figure 14 shows that the cement board did not reach the failure strain of about 0.003.

Specimen 3 was designed specifically to fail due to crushing of the cement board material. Failure was much more sudden in this mechanically fastened specimen. Where Specimen 2 had slight load drops with each fastener failure, Specimen 3 had a sudden load drop at 5,120 lb where the cement board crushed, which equates to a normalized load of 3,838 lb/ft width (Figure 15). Deflection was significantly less in this mechanically fastened specimen with a final failure deflection of 1.51 inches. No popping sounds were heard throughout the test which indicates the fasteners on the interface did not reach their failure loads. Figure 14 shows that the cement board exceeded the typical failure strain of 0.003.

Both normal concrete specimens failed as a shear debonding failure directly above one or more of the flanges of the FRP plank. Specimen 4 failed gradually over the last 20% of the total deflection. The failure began at a load of about 3,500 lb and the ultimate failure load was 3,800 lb with about 1.01 inches of deflection. The load equates to a normalized load of 2,849 lb/ft width. A debonding failure occurred over all four flanges at the south end of the specimen (Figure 16). No debonding could be seen at the north end of the specimen. Strain data indicates the concrete was not near the 0.003 failure strain (Figure 14).

Specimen 5 experienced a debonding failure that occurred in a much more sudden fashion. The specimen reached a deflection of about 0.73 inches and a load of 3,410 lb before a sudden load drop of 600 lb occurred. This equates to a normalized load of 2,555 lb/ft width. In this specimen, the debonding failure could only be seen over one flange on the south end of the specimen (Figure 17). Again, no debonding failures could be seen on the north end of the specimen. In addition to the debonding cracks in the concrete, tensile cracks could be seen in the concrete under the load line. The tension cracks penetrated about half the thickness of the concrete starting from the bottom and moving upwards. Strain data indicates the concrete was not near the 0.003 failure strain (Figure 14).

The next two tests were performed to test the performance of the FRP plank alone. The FRP plank is designed to be used with the Ts down, but since the specimens in this research use the FRP with the Ts up, tests were performed with the FRP in both orientations. Specimen 6, Ts up, produced a buckling failure in flange 1 at a load of 2,010 lb and a deflection of 2.09 inches (Figure 18). This load equates to a normalized load of 1,506 lb/ft width. Specimen 7, Ts down, produced a tensile failure in the FRP in flange 2. Before failure, the FRP plank was able to reach a load of 3,950 lb with a deflection of 4.27 inches (Figure 19). The load equates to a normalized load of 2,959 lb/ft width.

The final test performed was on the timber specimen (Specimen 8). This specimen was tested with the intent of providing information for comparison to the decking currently used in design. The timber specimen failed by a bending tension crack which occurred below the load point on the west edge of the specimen (Figure 20). The maximum load held by the timber specimen was 4,740 lb at a deflection of 1.54 inches. This equates to a normalized load of 5,030 lb/ft width.

Weight Comparison

When comparing the weights, it is necessary to compare the weight per square foot because the total weights between the timber and other specimens are not comparable due to differences in sizes. The weights are very comparable between the cement board with FRP plank specimens and the timber as seen in Table 1. The cement board and FRP plank specimens weigh only about 0.3 lb/ft^2 more than the timber with consistency because the cement board and FRP are factory produced. The only variance can be seen in the type of bond used. Specimen 3 weighs more than Specimen 2 because more mechanical fasteners were used in Specimen 3. On the other hand, the concrete and FRP plank specimens weigh more than twice as much as the timber per square foot. In addition, there is a significant difference in weight between Specimen 4 and Specimen 5 which resulted from the difficulty in achieving a uniform concrete thickness in the specimens cast in the laboratory. Finally, the FRP plank alone is only about 1/3 the weight per square foot of the timber.

Cost Comparison

Cost is an important factor in implementation of new designs within industry. The material for timber decks in pedestrian and light-weight vehicle bridges generally costs around \$4.25 - \$4.50 per square foot. The FRP pultruded plank used in this study costs about \$5.50/ft^2. According to USG, the cement board used in this study costs about \$3.25/ft^2. Concrete, on the other hand, is inexpensive when compared to the cement board costing only \$83.89/yd^3 which equates to \$0.26/ft^2 in this study ("Construction," 2006). The least expensive of the hybrid panels were Specimen 4 and Specimen 5. Using only concrete and the FRP plank, a total estimated cost of \$5.76/ft^2 is found. This cost does not include the cost of the epoxy which is unknown. Specimen 1 was the least expensive of the cement board and FRP plank panels. Costing \$8.75/ft^2, Specimen 1 costs about \$3.00/ft^2 more than the concrete and FRP plank panels. Specimen 2 and Specimen 3 were the two most expensive panels tested. The estimated cost of Specimen 2 was \$9.42/ft^2 with the mechanical fasteners costing \$5.00 per 75 pieces amounting to \$0.67/ft^2 because one whole pack was used in fabricating the specimen. Specimen 3 had an estimated cost of \$10.00/ft^2 with the mechanical fasteners costing \$6.78 per 200 pieces amounting to \$1.25/ft^2 when using 270 pieces to create the specimen. See Table 1 for the estimated cost of each specimen. No labor costs involved with assembling the hybrid panels were included in the estimated costs.

Ultimate Load Comparison

The ultimate load comparison can be made by looking at the normalized maximum moments able to be reached by each specimen. Looking at Figure 21, it is evident that the timber specimen has the greatest moment capacity of all specimens. Specimen 1 and Specimen 3 have large load capacities because they have the best bond at the shear interface producing close to fully composite action between the two materials. Specimen 3 failed by cement board crushing indicating the shear bond was maintained throughout the test and specimen 1 failed by debonding at a point close to cement board crushing. Specimen 2 experienced significant slip at the shear bond interface allowing this specimen to achieve a maximum moment only 57% that of the timber. Specimen 2 reached 75% of the load of Specimen 3. Both specimens used mechanical fasteners at the shear bond interface, but Specimen 3 was designed to fail via cement board crushing. This information could be useful in designing an efficient mechanical fastener specimen which can achieve an efficient stiffness and load carrying capacity. The concrete specimens have maximum moments about 54% that of the timber, but still have the ability to hold a wheel load of 1,000 lb with a safety factor of over 2.5. The FRP specimens produced significantly different results due to stability factors. Specimen 6 was arranged with the Ts up allowing buckling to be a factor in the load carrying capacity. Specimen 6 was only able to reach a load about 50% of Specimen 7. Specimen 7 reached a moment capacity comparable to the two concrete specimens.

Stiffness Comparison

Using the slope of the load versus deflection curves, the effective stiffness of the different specimens can be compared (Figure 22). This stiffness can be used for design purpose to ensure deflection limits are not exceeded when designing the deck of the bridge. To find the effective stiffness, the slopes of the different load versus deflection curves were used in the equation

$$EI = \frac{P}{\delta}\frac{L^3}{48}$$

where

$EI =$ Effective stiffness of specimen per foot width (lb-in^2/ft)

$\frac{P}{\delta} =$ Slope of load versus deflection diagram (lb/ft/in)

$L =$ Span length between supports (66 inches).

Table 3 shows the effective stiffness of each of the specimens. Once the effective stiffness of each specimen had been determined, comparisons of deflection criteria could be made. As seen in Figure 22, supporting beam or truss spacing for the decking was computed based on deflection limits and the effective stiffness of each specimen as calculated based on the normalized test data. The largest support spacing can be achieved using the normal weight concrete with the FRP plank. On average, it was found that the normal weight concrete with the FRP plank could achieve support spacing about 6% wider than timber. Both normal concrete tests provided similar results with respect to the effective stiffness of the two specimens. The epoxy-bonded cement board was found to allow about the same support spacing as the timber. The two mechanically fastened specimens produced very different results. The mechanically fastened specimen designed to fail via the fasteners at the shear interface yielded support widths only 62% of timber. On the other hand, the mechanically fastened specimen designed to fail via cement board crushing yielded support widths 91% of timber. Neither mechanically fastened specimen was able to achieve an effective stiffness similar to that of timber. The effective stiffness of both FRP plank specimens was found to be significantly smaller than the timber. Both specimens could achieve support widths only about 60% of what timber is capable of spanning based on deflection limits.

Conclusions

The investigation of a hybrid FRP pultruded plank with a concrete compression flange for use in pedestrian or light-weight vehicle bridges was conducted via experimental studies. Through these studies, it was found that the hybrid panels composed of pultruded plank and normal weight concrete produced results similar to that of traditional timber decking. The timber achieved greater strengths than all specimens aside from the epoxy-bonded cement board, but the normal weight concrete specimens were able to achieve a greater stiffness than the timber specimen. With the increased durability associated with the hybrid panels, and with additional research, it could be found practical to incorporate the hybrid panel into pedestrian or light-weight vehicle bridge deck design. To further improve the design of the hybrid panels, light-weight concrete could be used in place of normal weight concrete to decrease the weight of the deck. In addition, if a sand grit surface was epoxied to the Ts, the bond between the concrete and FRP may be improved further from the already proven effective method of applying wet concrete to wet epoxy. The epoxy-bonded cement board specimen also performed similar to the timber, but questions about the cement board durability could prevent this specimen from being used in exterior applications. The mechanically-fastened specimens need more research before being considered in design. Specimen 3 was able to achieve strengths similar to Specimen 1, and Specimen 2 failed in a ductile manner which can be beneficial in providing a warning of failure. More research could produce a mechanically fastened specimen which fails in a ductile manner yet achieves acceptable strengths. It is important to note that while the concrete specimens performed better than the cement board specimens; the concrete thickness was 1 inch, whereas the cement board thickness was only ¾ inch. This fact, along with the higher modulus of elasticity achieved by the concrete, could explain the superior stiffness performance in the concrete specimens. Currently, cost could hold the hybrid panel from being implemented into design, but if the life span can be proven to be twice that of timber, then the initial cost would be balanced by the durability of the hybrid panel.

Acknowledgements

Special thanks are due to Strongwell for donating the FRP pultruded planks for the project and USG for donating the cement board used in the study. In addition, special thanks are in order for John Dreger and Bill Lang of the Wisconsin Structures and Materials Testing Lab for their help in setting up tests and ordering materials.

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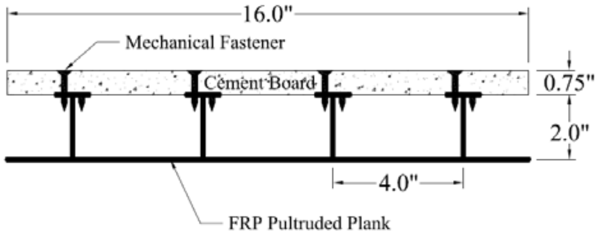

Figure – 1. Dimensioned design drawing of cement board specimen with mechanical fasteners as the shear transfer mechanism.

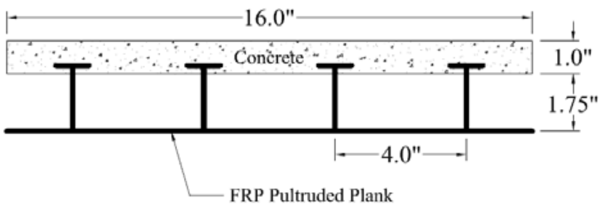

Figure – 2. Dimensioned design drawing of concrete specimens.

Figure – 3. Mechanically fastened cement board specimen displaying fastener layout (Specimen 3).

Figure – 4. Concrete specimen displaying FRP flanges embedded in concrete (Specimen 4).

Figure – 5. Formwork for concrete specimens with wet concrete prior to setting (Specimen 4).

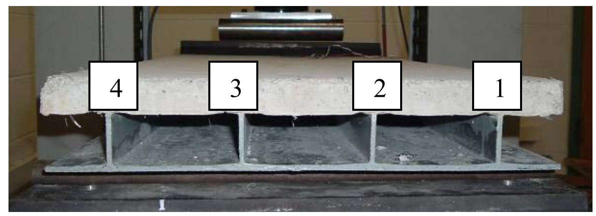

Figure – 6. Web labels from north end of specimen (Specimen 4).

Figure – 7. Experimental set-up (Specimen 4).

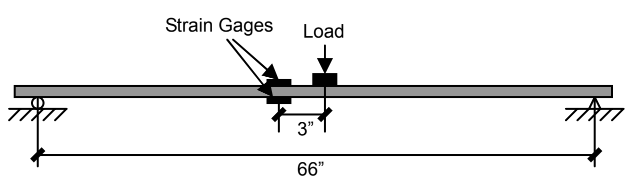

Figure – 8. Instrumentation of specimens with strain gages.

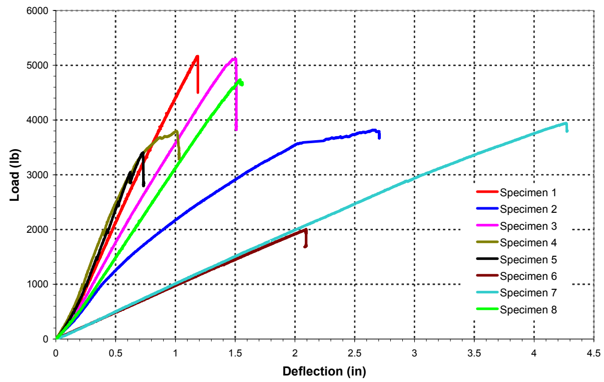

Figure – 9. Load vs. deflection graph for different specimens (Raw data).

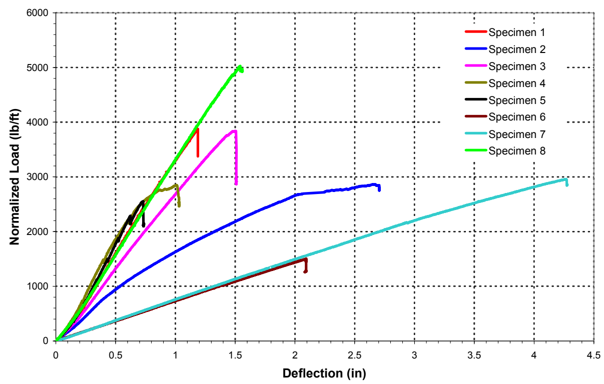

Figure – 10. Normalized load vs. deflection graph for different specimens.

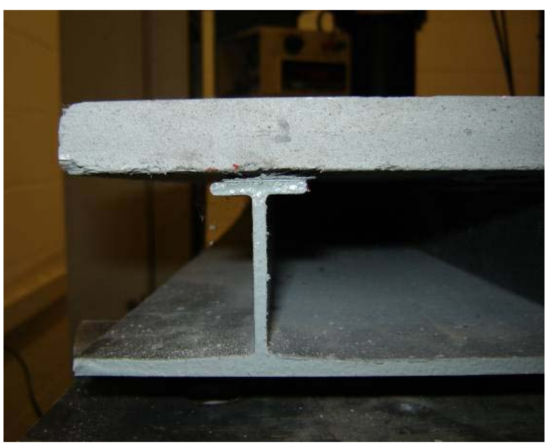

Figure – 11. Debonding failure in epoxy-bonded cement board specimen (Specimen 1).

Figure – 12. Epoxy-bonded specimen cut to reveal debonding failure (Specimen 1).

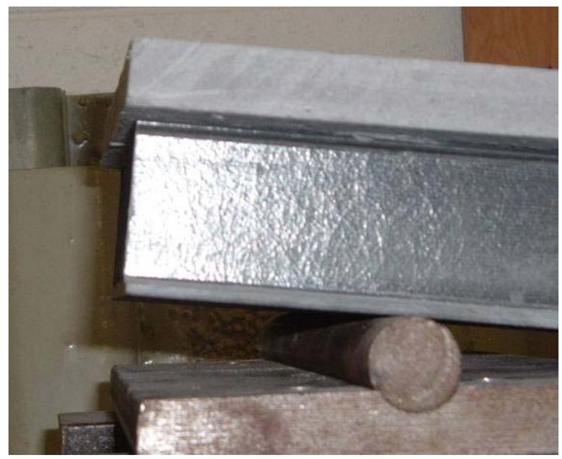

Figure – 13. Slip witnessed during gradual failure of mechanical fasteners (Specimen 2).

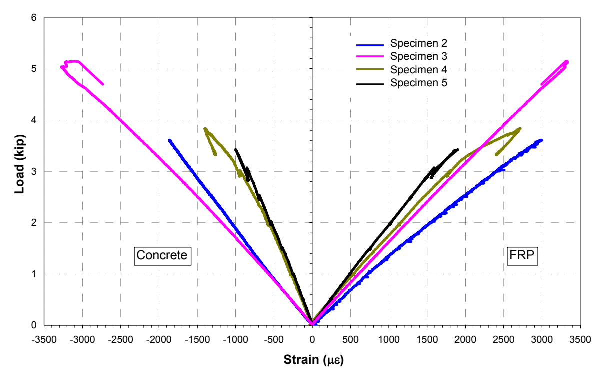

Figure – 14. Strain data for specimens.

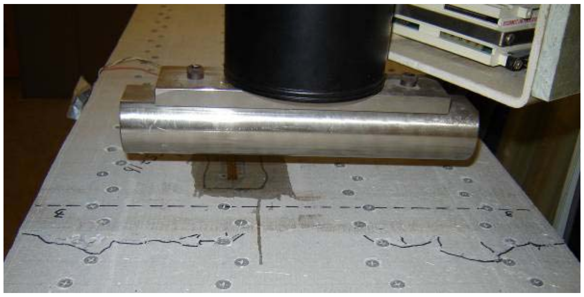

Figure – 15. Cement board crushing observed in second mechanical fastener test (Specimen 3).

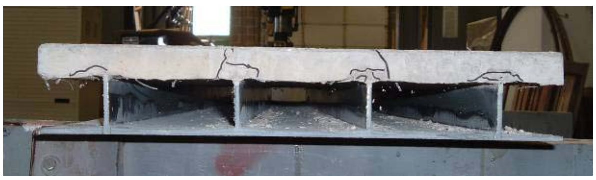

Figure – 16. Debonding failure observed in first concrete specimen (Specimen 4).

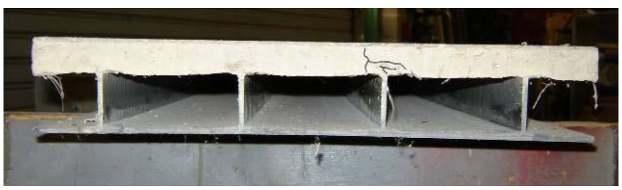

Figure – 17. Debonding failure observed over web 2 of second concrete specimen (Specimen 5).

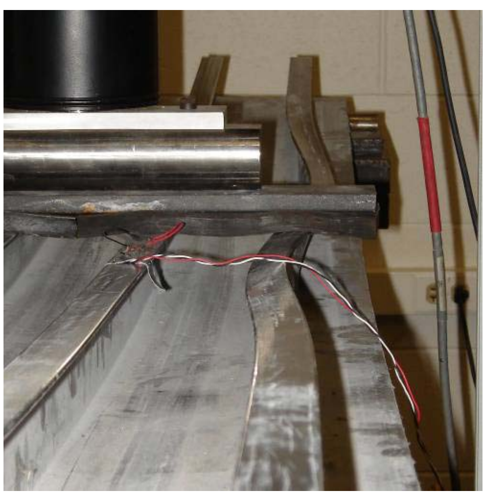

Figure – 18. Buckling failure in FRP plank with Ts up (Specimen 6).

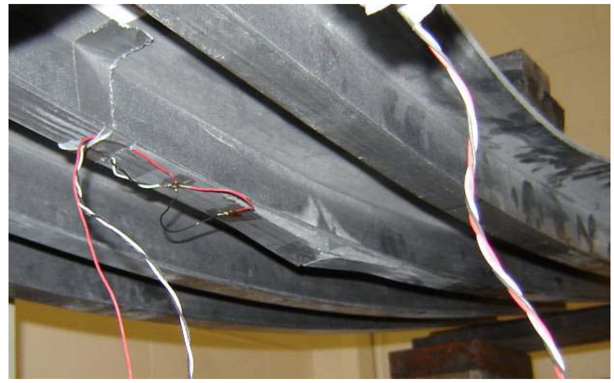

Figure – 19. Tensile failure in flange 2 in FRP plank specimen with Ts down (Specimen 7).

Figure – 20. Bending tension failure seen in timber (Specimen 8).

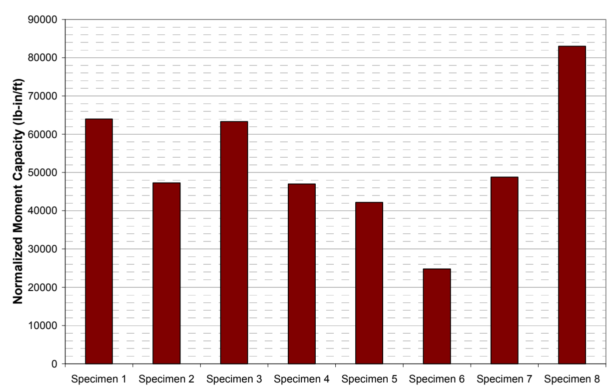

Figure – 21. Specimen moment capacities.

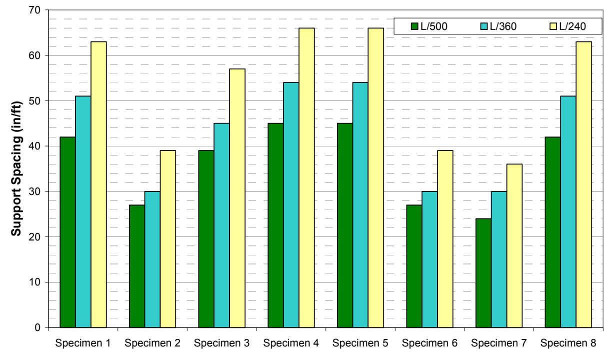

Figure – 22. Maximum support widths for 1,000 lb wheel load based on deflection limits.

Table – 1. Details of specimens and weight comparison.

Specimen Number	Composition	Bond Type	Weight (lb)	Weight per Square Foot (lb/ft^2)	Estimated Cost* (\$/ft^2)
1	Cement board and FRP pultruded plank	Epoxy	56.0	6.9	8.75
2	Cement board and FRP pultruded plank	Self-tapping Screws	54.5	6.7	9.42
3	Cement board and FRP pultruded plank	Cement board screws	55.7	6.9	10.00
4	Concrete (3/8" coarse aggregate size) and FRP pultruded plank	Concrete Bond and Epoxy	115.5	14.2	5.76
5	Concrete (3/8" coarse aggregate size) and FRP pultruded plank	Concrete Bond and Epoxy	106.7	13.1	5.76
6	FRP pultruded plank Ts Up	N/A	18.9	2.3	5.50
7	FRP pultruded plank Ts Down	N/A	18.9	2.3	5.50
8	Timber (Select Grade Douglas Fir)	N/A	39.6	6.5	4.25 - 4.50

*Cost of epoxy and labor not included in estimated cost.

Table – 2. Specimen test results.

Specimen	Failure Load (lb)	Failure Load per foot width (lb/ft)	Deflection @ Failure (in)	Compression Strain @ Failure ($\mu\varepsilon$)	Tensile Strain @ Failure ($\mu\varepsilon$)
1	5,180	3,877	1.19	NR	NR
2	3,820	2,864	2.67	-1,930	3,440
3	5,120	3,838	1.51	-3,220	3,330
4	3,800	2,849	1.01	-1,400	2,710
5	3,410	2,555	0.73	-1,000	1,900
6	2,010	1,506	2.09	-7,180	2,090
7	3,950	2,959	4.27	-4,750	12,730
8	4,740	5,030	1.54	NR	NR

NR = Not Recorded

Table – 3. Calculated effective stiffness and moment capacity.

Specimen	Effective Stiffness per foot width (kip-in^2/ft)	Maximum Moment (lb-in/ft)
1	20,530	64,000
2	7,820	47,300
3	16,260	63,300
4	23,540	47,000
5	23,220	42,200
6	4,320	24,800
7	4,240	48,800
8	20,270	83,000