AGGREGATE-COATED FRP PLANK AS FORMWORK AND CRACK CONTROLLING DEVICE FOR REINFORCEMENT-FREE BRIDGE DECKS

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ABSTRACT

This research describes usage of aggregate coated fiber reinforced polymer (FRP) plank as stay-in-place (SIP) formwork and crack controlling device for reinforcement-free concrete bridge decks on precast concrete girders. The design concept for a reinforcement-free bridge deck utilizes compressive membrane action in the deck to resist wheel loads by tying girders together combines. This allows removal of flexural steel reinforcement while introducing a polypropylene fiber reinforced concrete to control thermal and shrinkage cracks, and employing aggregate coated FRP planks as a SIP formwork and also as a flexural crack controlling device. The usage of the FRP plank allows construction of more innovative, cost effective, durable and rapid concrete decks on highway bridge girders. Experimental research including testing of FRP planks to assure that the planks have sufficient capacity to serve as a formwork and testing of concrete beam specimens cast on the aggregated coated FRP plank to investigate bonding behaviour at the plank-concrete interface and flexural crack controlling ability of the plank. A pilot bridge was built in Wisconsin, U.S.A. and this case study showed that the usage of the FRP plank and reinforcement-free bridge deck concept improved productivity of the bridge decks over 4 times in terms of construction of the unit deck area per man hours compared to conventional bridge decks.

KEY WORDS

Formwork, FRP plank, pultruding, bridge decks, flexural crack control, stay-in-place formwork, reinforcement-free deck.

INTRODUCTION

Fiber reinforced polymer (FRP) panels used as formwork for concrete slabs may have many applications but is being used particularly successfully for highway bridge decks. The recent availability of FRP stay-in-place (SIP) forming materials coincided with the introduction of a new reinforcement free highway bridge deck system (Oliva et al. 2007). A new load carrying mechanism was employed to eliminate the conventional steel reinforcement. The mechanism is a combination of compressive membrane action (Ockleston 1955, 1958 and Park 1964, 1965) in the deck obtained by tying girders together and utilizing the high lateral stiffness of wide flanged concrete girders for restraint. Polypropylene fiber reinforced concrete (FRC) is introduced to control shrinkage cracks. Aggregate-coated pultruded FRP plank provides the deck formwork and also acts as a deck crack controlling system (Figure 1).
Placement of the FRP plank is much simpler than common wood formwork because it is pre-fabricated and light enough to be placed in panels by a single worker. Besides creating a simple and quickly built form, other advantages are intrinsic in the system. If the FRP plank is left in place after the construction, i.e. as an SIP form, then the process of formwork removal is eliminated. Bridge contractors have identified removal of traditional wood deck forming as one of the most hazardous tasks in bridge building because crews are working in high positions, working on materials overhead, and removing heavy components from above. Using SIP forms eliminates this dangerous task and improves workzone safety. A third advantage that FRP plank forming can provide is increasing the durability of the concrete deck by reducing concrete cracking. If special methods are employed to increase the bond between the FRP and concrete, the continuous FRP plank form can provide better crack control than discreet reinforcing bars in the concrete. One particular type of FRP plank will be described here. It is a commercially available product that was developed originally for use as floor and scaffold planking to replace heavier wood planks. First, a research study examined the FRP plank to measure its static properties when used as formwork and its ability to provide crack control for concrete in flexure. Finally, the formwork was employed in the construction of a reinforcement-free deck that was the subject of a case study.

FRP PLANK FORMWORK MATERIAL

When used as formwork, the FRP Plank is actually placed upside down compared to the position used for scaffolding planks. Figures 2-3 show a worker placing a 305 mm wide piece of FRP plank form panel and a closeup of the panel with ribs. The actual dimensions of the FRP cross section are shown in Figure 4.

The FRP plank is produced in 305 mm and 610 mm widths and is normally used in walkway or flooring applications with the flat side facing up and a smooth inner surface on the bottom side. Two types of stone aggregate, sand and gravel, were bonded to the inner flat surface of the plank to improve the bond between the concrete and the FRP plank as shown in Figure 3. The aggregate was bonded with epoxy to the FRP plank and cured prior to use as formwork. Longitudinal tension tests were conducted on the FRP plank material yielding a longitudinal tensile strength, $\sigma_L = 480$ MPa and a longitudinal modulus of elasticity, $E_L = 26,890$ MPa (Ringelstetter et al. 2006).

EXPERIMENTAL RESEARCH

Testing of FRP plank with a simulated static foot loading

A simulated static foot loading was applied to four FRP planks with 305 mm width joined together representing the field condition. A 25.4 mm thick neoprene pad was used for the loading pad contacting the bottom flange of
the specimen. A 76.2 mm thick wood block was used to transfer the load between steel loading head and the neoprene pad. There is a strong side and weak side at the joint of the FRP planks since adjacent planks actually partially “lock” together through a clip flange built into the sections at the joint as shown in Figure 5.

![Figure 5. Joint of the FRP plank](image)

The load was applied at the strong side of a specimen for the first experiment and at the weak side of the other specimen for the second experiment as shown in Figure 6. The span of the specimens was 0.914 m. The loading for the two tests was located at the center of the span near the center joint in between the ribs. The specimens were in a simply supported configuration.

The failure mode during the strong side loading was punching failure of the bottom flange (Figure 6(a)) while the failure mode for the weak side loading was a separation of the joint (Figure 6(b)). With the weak side load the panel could resist additional force after the separation of the connection but the separation was considered as a failure since the formwork loses its function. The capacities of the specimens were 7.26 kN for strong side loading and 3.81 kN for weak side loading indicating that the FRP plank has sufficient capacity to resist the weight of a worker.

![Figure 6. Strong side and weak side loading specimens after testing.](image)

**Testing of concrete beam specimen reinforced by FRP plank**

Five 203 mm wide by 178 mm deep beams (specimens F1-F5) with different lengths were fabricated using the aggregate-coated FRP plank as a bottom formwork for the concrete (Table 1). No other tensile or shear reinforcement was used in the beams. Figure 4 shows the approximate cross section dimensions of a two-legged portion of the FRP plank that was used in the tests. The 203 mm wide portion was cut from the center of the 305 mm wide FRP plank.

One control specimen (FC1) was made up of the FRP form and concrete beam without any aggregate attached to the form surface. The second control specimen, a steel reinforced beam, FC2 in Table 1, was a conventional steel reinforced concrete beam on a 1.83 m span, with no shear reinforcement and no FRP plank. The beam was reinforced with ASTM Grade 60 steel rebars (141 MPa nominal yield strength) with 38 mm of clear bottom cover. This reinforcement quantity was the same as that needed for the bottom transverse reinforcement in a steel reinforced bridge deck with a 0.914 m clear span between girders (the edge of girder flange to the edge of adjacent girder flange).
The load was applied at the center of the specimen in a three point bend test configuration by a hydraulic actuator under manual displacement control. The initial flexural cracking load was identified by observing the change in slope of the load-strain curves and verified by visual inspection. The initial cracking loads are shown in Table 2. All the initial cracks were observed near the center of the specimens. The loads obtained from each test were converted to give the cracking moment and normalized with respect to a 27.6 MPa compressive strength concrete to account for the differences in the concrete strengths of the various beams.

The beams (specimens F1-F5) with the aggregate coated FRP planks showed higher initial cracking capacities compared to the control specimen reinforced by the FRP plank with the smooth surface (specimen FC1) and compared to the specimen with the steel reinforcing bars (specimen FC2). This indicates that coated FRP plank can produce an increase in the initial cracking moment capacity of a concrete beam, which may be a serviceability benefit for a reinforced concrete section, particularly a bridge deck. The beams with the sand-coated FRP plank (specimen F2 and F3) showed higher initial cracking capacity than the specimen with the gravel-coated FRP plank (specimen F1), indicating that sand coating provides a more even bond than the gravel in the interface region.

Current design codes allow a concrete structure to crack under service loads, however, the width of the cracks is typically limited to a prescribed value or spacing of reinforcing bars is limited to achieve the same effect. The aggregate-coated FRP may have the ability to better distribute cracks which would lead to narrower crack widths. This is provided that no slip or very little slip occurs at the interface between the FRP plank and the concrete. A comparison of the numbers of cracks was, therefore, an important evaluation criterion in this study. The number of flexural cracks was counted after the failure of each specimen (Table 2). The similarity in the number of cracks clearly shows that the aggregate coating provides a mechanism to transfer bond stresses at the interface between the FRP plank and the concrete. A comparison of the numbers of cracks was, therefore, an important evaluation criterion in this study. The number of flexural cracks was counted after the failure of each specimen (Table 2). The similarity in the number of cracks clearly shows that the aggregate coating provides a mechanism to transfer bond stresses at the interface between the FRP plank and the concrete. The number of cracks in specimens F4, F5 and FC2 demonstrates that the aggregate-coated FRP plank can serve as an effective means to distribute flexural cracks in a similar manner to internal steel reinforcements as shown in Figure 7. The specimens reinforced by the aggregate coated FRP planks failed in a number of different modes. The failure modes were shear failure for specimens F1-F3, flexural failure with a significant slip at the interface of the FRP plank and the concrete for specimen FC1,

### Table 1. Properties of flexural test beams

<table>
<thead>
<tr>
<th>Specimen I.D.</th>
<th>Span (m)</th>
<th>Tensile Reinforcement</th>
<th>Compressive strength of concrete (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>1.09</td>
<td>Gravel coated FRP plank</td>
<td>25.8</td>
</tr>
<tr>
<td>F2</td>
<td>1.09</td>
<td>Sand coated FRP plank</td>
<td>25.8</td>
</tr>
<tr>
<td>F3</td>
<td>1.09</td>
<td>Sand coated FRP plank</td>
<td>24.5</td>
</tr>
<tr>
<td>FC1*</td>
<td>1.09</td>
<td>FRP plank</td>
<td>25.8</td>
</tr>
<tr>
<td>F4</td>
<td>1.83</td>
<td>Sand coated FRP plank</td>
<td>32.1</td>
</tr>
<tr>
<td>F5</td>
<td>1.83</td>
<td>Sand coated FRP plank</td>
<td>33.5</td>
</tr>
<tr>
<td>FC2*</td>
<td>1.83</td>
<td>Steel reinforcement (3-#3)</td>
<td>32.9</td>
</tr>
</tbody>
</table>

* *Control specimens*

### Table 2. Test measurements from flexural beam tests

<table>
<thead>
<tr>
<th>Specimen I.D.</th>
<th>Span (m)</th>
<th>Initial cracking load (kN)</th>
<th>Normalized initial cracking moment* (kN-mm)</th>
<th>Failure load (kN)</th>
<th>Deflection at failure load (mm)</th>
<th># of flexural cracks at both side</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>1.09</td>
<td>15.6</td>
<td>4395</td>
<td>63.2</td>
<td>3.556</td>
<td>11</td>
<td>Shear</td>
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<tr>
<td>F2</td>
<td>1.09</td>
<td>20.9</td>
<td>5909</td>
<td>66.7</td>
<td>4.216</td>
<td>9</td>
<td>Shear</td>
</tr>
<tr>
<td>F3</td>
<td>1.09</td>
<td>22.2</td>
<td>6451</td>
<td>57.4</td>
<td>4.216</td>
<td>9</td>
<td>Shear</td>
</tr>
<tr>
<td>FC1*</td>
<td>1.09</td>
<td>15.1</td>
<td>4271</td>
<td>16.9</td>
<td>0.432</td>
<td>3</td>
<td>Flexure</td>
</tr>
<tr>
<td>F4</td>
<td>1.83</td>
<td>12.5</td>
<td>5276</td>
<td>59.6</td>
<td>16.993</td>
<td>22</td>
<td>Hybrid</td>
</tr>
<tr>
<td>F5</td>
<td>1.83</td>
<td>12.0</td>
<td>4983</td>
<td>65.8</td>
<td>17.907</td>
<td>29</td>
<td>Hybrid</td>
</tr>
<tr>
<td>FC2*</td>
<td>1.83</td>
<td>8.0</td>
<td>3356</td>
<td>38.3</td>
<td>8.557(Y)** 54.483(U)</td>
<td>22</td>
<td>Flexure</td>
</tr>
</tbody>
</table>

* *Normalized moment to concrete with 27.6 MPa compressive strength by multiplying √(fc'/27.6MPa) with 4316 kN-mm the design service load moment for a 0.914m clear span deck, including impact, from U.S. design practice.

** Values given for yield (Y) and ultimate (U) deflection.
hybrid flexural/shear failure for specimens F4-F5 and flexural failure with yielding of the steel rebars followed by concrete crushing for specimen FC2. A complete description of the beam performance including strain and capacity data may be found in a report by Bank et al. (2007).

Figure 7. Cracking comparison for FRP specimen F5 (top) and steel reinforced FC2 (lower)

CASE STUDY: HIGHWAY BRIDGE DECK CONSTRUCTION WITH FRP FORMWORK

The construction of a highway bridge with a unique reinforcement-free deck, over wide flanged precast concrete girders, provided an ideal opportunity for using the FRP planks as forming panels between the closely spaced girder flanges. The Wisconsin Department of Transportation (WisDOT) in cooperation with the University of Wisconsin employed the FRP SIP formwork for a bridge replacement project on U.S. Highway 12 in Wisconsin. The bridge is on a two lane highway with sidewalks and spans 30.5 m with a single span superstructure. For the FRP plank and the concrete to act as a “composite” structural member a satisfactory bond at the interface between the smooth surface of the pultruded plank and the concrete must be developed. To achieve this bond, the FRP manufacturer created an interface on the plank with sand epoxied to the bonding surface as used in the flexural beam tests described earlier. The FRP planks were also pre-cut in length to exactly fit the span between the girder flanges while being seated in a recessed edge of the flange. The SIP form panels were quickly set into place and the recesses placed in the edges of the girder flanges to meet the forms prevented the panels from slipping off (Figure 8 (a)). On this bridge the contractor chose to glue the panels down to prevent possible uplift if strong winds occurred prior to pouring the deck concrete.

Placement of the stay-in-place FRP form panels was accomplished much quicker than the time normally required for construction of wood formwork. On previous projects in Wisconsin, an average placement time of 86 worker minutes per 0.83 m² of form surface was required on the job for construction and placement of wood forming. The FRP form panels for the Highway 12 bridge were placed in 4.2 worker minutes per 0.83 m², twenty times faster than the wood forming time. Though the labor and placement time for the FRP forming is less than conventional formwork, the material cost is higher. Conventional wood formwork costs approximately $5.00 per 0.83 m² for materials and placement. In comparison the FRP SIP formwork cost $5.50 per 0.83 m² for materials before the sand bond coat was epoxied in place, and $9.50 per 0.83 m² with the sand coat. The value of the FRP SIP formwork, however, cannot be judged by the comparative material cost alone. Additional benefits, which are more difficult to associate with a direct cost figure, include:

1. faster erection allowing reduced construction time and less exposure of workers to work-zone traffic dangers,
2. elimination of the dangerous form removal operations and increased worker safety, and
3. improved concrete bridge deck durability through crack control provided by the FRP formwork.
This case study showed that the usage of the FRP plank and reinforcement-free bridge deck concept improved productivity of the bridge deck over 4 times in terms of construction of the unit deck area per man hours compared to conventional bridge decks.

In this project the use of FRP SIP formwork was a successful design element. Construction was simplified and construction time reduced. After being in service for a two years no deck cracking has been detected by special gauges placed internally during the construction. In addition, after the first phase deck concrete pour, the contractor’s safety administrator praised the system because of the safe working surface during concrete placement and elimination of the dangerous form removal process where many of the reported worker injuries occur.

SUMMARY AND CONCLUSIONS

An existing commercial FRP floor and scaffolding plank was examined to determine whether it could also efficiently serve as a stay-in-place form and crack controlling device for concrete bridge decks. The examination included measuring the plank’s construction load capacity and the contribution of the FRP to providing crack control. Then the new FRP forming system was used in a case study for construction of a bridge deck on a U.S. trunk highway. FRP stay-in-place forms proved to be a very attractive alternate to traditional wood formwork based on the specific observations and conclusions listed below,

(1) The FRP plank performs very well as a form material resisting construction loads. It can resist concentrated loads of construction workers with a capacity of 3.8 kN over a footprint sized area.

(2) When a layer of sand is bonded to the top flat surface of the FRP plank, the FRP becomes composite with the concrete deck. Using this composite action, the FRP plank is as effective at providing crack control under flexure as the normal amount of black reinforcing steel used in bridge decks. If the bridge deck reinforcing was epoxy coated, the FRP would provide superior crack control (limiting size of cracks and increasing number of cracks) compared to the steel reinforcing.

(3) The aggregate-coated FRP SIP formwork provides four important benefits when used in the field to build a concrete deck: 1) faster erection allowing reduced construction time and less exposure of workers to work-zone traffic dangers, 2) elimination of the dangerous form removal operations and increased worker safety, 3) improved concrete bridge deck durability through crack control provided by the FRP formwork, and 4) improved productivity for the bridge superstructure construction over 4 times in terms of the unit deck area per man hours compared to conventional bridge decks.

FRP formwork is likely to be more expensive than traditional wood forms, with material costs of two to three times wood, but it must be evaluated on the basis of the benefits listed above in addition to material cost.

REFERENCES


