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pultruded planks in pedestrian bridge decks where the pultruded plank is used with a cement board to produce a hollow slab of 75 mm depth that is typical of timber decking used in FRP pedestrian bridges. Tests were conducted on beam-type specimens of the hybrid slabs to investigate the load transfer mechanisms between the pultruded plank and the cementitious "overlays" for both the 75 mm and 200 mm depths. The load carrying and failure mechanisms of the hybrid slabs were studied and it was concluded that such hybrid slabs are viable systems for both highway and pedestrian bridge decks. A bridge deck using the 200 mm deep hybrid slab system was recently constructed on a highway in Wisconsin, USA.
July 1, 2009

Prof. M.C. Forde, Editor-in-Chief:
Construction and Building Materials
University of Edinburgh,
Infrastructure and Environment,
School of Engineering and Electronics,
The Kings Buildings,
Edinburgh, EH9 3JL,
Scotland, UK

RE: New Submission

Dear Prof. Forde:

I am submitting the manuscript entitled “Hybrid Concrete and Pultruded-Plank Slabs for Highway And Pedestrian Bridges,” by Lawrence C. Bank, Michael G. Oliva, Han-Ug Bae, and Bryan V. Bindrich” for publication in Construction and Building Materials.

The paper is an original work and has not been published elsewhere nor submitted for publication elsewhere.

Sincerely,

[Signature]

Lawrence C. Bank
Professor
HYBRID CONCRETE AND PULTRUDED-PLANK SLABS FOR HIGHWAY AND PEDESTRIAN BRIDGES

Lawrence C. Bank, Michael G. Oliva, Han-Ug Bae, and Bryan V. Bindrich

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ABSTRACT

Studies on two novel uses of hybrid structural members consisting of commercially produced glass reinforced pultruded ribbed fiber reinforced polymer (FRP) planks and concrete are discussed in this paper. Pultruded planks are produced by all the major pultruders in the world are used primarily as decking for platforms. They are highly optimized and have the potential to be used in many other infrastructure applications. However their flexural stiffnesses have generally been too low to be used in highway and and pedestrian bridges due to current spans requirements in these structures. However, when used “compositely” with concrete or cementitious materials in a hybrid form they have the potential to be much more widely used. Two Research studies conducted on two possible hybrid systems of different structural depths are discussed in this paper. The first study describes the use of pultruded planks as permanent formwork in highway bridge decks where the plank is used with concrete slab to produce a solid slab with a depth of 200 mm that is typical of slabs seen in highway bridge decks.
The second study describes the use of pultruded planks in pedestrian bridge decks where the pultruded plank is used with a cement board to produce a hollow slab of 75 mm depth that is typical of timber decking used in FRP pedestrian bridges. Tests were conducted on beam-type specimens of the hybrid slabs to investigate the load transfer mechanisms between the pultruded plank and the cementitious “overlays” for both the 75 mm and 200 mm depths. The load carrying and failure mechanisms of the hybrid slabs were studied and it was concluded that such hybrid slabs are viable systems for both highway and pedestrian bridge decks. A bridge deck using the 200 mm deep hybrid slab system was recently constructed on a highway in Wisconsin, USA.

**INTRODUCTION**

Glass fiber reinforced polyester and vinyllyester resin ribbed pultruded planks are produced by most large commercial pultrusion companies for use in FRP platforms and stair systems. In the USA these are known by their trade names, such as SAFPLANK® and SAFDECK® by Strongwell, SuperPlank™ and Tuf-dek™ by Creative Pultrusions, and Deckboard by Bedford Reinforced Plastics. Fig. 1 shows 12 in (300 mm) and 24 in (600 mm) wide SAFPLANK sections.

The pultruded planks typically have a proprietary tongue-and-groove type longitudinal edge that allows them to be assembled into a large platform or deck system. They can be supplied with an epoxy-bonded grit surface on the upper plate to improve traction for walking. In the new applications to be described in this paper the pultruded planks are used in their inverted position with the solid plate facing downwards and the ribs facing upwards.
The first study discussed describes the use of the pultruded plank as a permanent, or stay-in-place, formwork system for concrete highway bridge decks having a depth of 200 mm. This is referred to as the 200 mm solid hybrid system. The second application discussed describes the use of the pultruded plank with a cement board to form a hollow or voided section that is 75 mm deep and can be used in place of timber decking for pedestrian bridges or walkways. This is referred to as the 75 mm hollow hybrid system.

200 MM SOLID HYBRID SYSTEM

Custom designed pultruded FRP panels (produced by Composite Deck Solutions) have been used as permanent formwork and reinforcement to construct highway bridge decks in two bridges in the USA (Reising et al. 2004; Berg, et al, 2006). Fig. 3 shows the stiffened profile of the FRP planks used in this application. In this case the FRP panels are substantially heavier and have much larger wall thicknesses than the commercially produced “off-the-shelf” ribbed planks described in this study. In the application described in Bank et al 2006, precast I-girders were spaced at 8 ft (2.4 m) and the pultruded forms needed to be able to carry the load of the 8 in (200 mm) deep concrete deck during casting and also serve as positive moment reinforcement after the concrete cured, making them relatively heavy and expensive. In this type of application the FRP deck forms are similar in function to partial-depth prestressed concrete formwork panels that have been used in bridge deck construction for many years. Keller and co-workers in Switzerland (2007) have studied a similar ribbed pultruded planks produced by Fiberline in
Denmark for bridge decks in which the concrete layer is composed of a light weight concrete core and a high strength concrete upper “flange” to create an optimal light weight hybrid deck.

In recent years many US Departments of Transportation have begun to use wide-flange bulb-T precast concrete girders. These girders, which are typically available in 54 or 72 in (1.35 or 1.8 m) depths, have top flanges that are 48 in (1.2 m) wide and can span up to 160 ft (48 m). Due to these large spans the clear gap between the girders usually varies between 1 and 3 ft (300 and 900 mm), which makes the use of conventional plywood forming and timber joists uneconomical due to the labor required to set-up and strip the forms. To provide a mechanism to contractors to use alternative formwork systems for such bridge decks a model specification for various non-structural permanent formwork options as alternatives to the plywood systems was developed (Bank et al, 2009). The study considered thin FRC panels, thin-grid concrete reinforced panels, FRP rebar reinforced panels and commercially available pultruded FRP planks. From this study it was concluded that commercially produced pultruded FRP planks could be safely used in gaps up to approximately 4 ft (576 mm) (depending on the plank) as permanent non-structural formwork for bridge deck construction with slabs of around (8 in) 200mm.

Based on this conclusion, pultruded FRP planks were selected for use in the design and construction of an innovative highway bridge deck in Black River Falls, Wisconsin (Oliva et al, 2007). The innovative structural system consisted of a continuous-reinforcement-free polypropylene fiber-reinforced concrete (FRC) deck that relied on arching action developed by external tension ties in the girder webs and the lateral stiffness of the girders themselves to carry the deck self weight and the concentrated wheel loads between the girders. The bridge was a
single span bridge with a length of 100 ft (30.5 m) and a skew of 13° and consisted of eight 54 in bulb-T girders spaced at 7 ft (1.925 m) on-center. The clear space between the girder flanges was 3 ft (900 mm). A pultruded FRP planks (SAFPLANK) was consider for this application.

For this application however, the pultruded plank did not only serve as a permanent form, but was also required to control longitudinal flexural cracking in the unreinforced deck above. In prior work on steel-free decks in Canada (Bakht and Lam, 2002) the development of a prominent longitudinal flexural crack between the girders was found to be a serviceability problem. Therefore tests were conducted at the University of Wisconsin to investigate the load transfer mechanism between the FRP plank and the concrete to determine if the pultruded FRP plank could serve to control the longitudinal cracking in the deck.

**Description of the Tests Conducted**

Since the pultruded FRP plank has a smooth surface it was clear that the plank would not be able to control the flexural cracking unless some bond stress could be developed between the concrete and the pultruded plank. To investigate this a number of tests were conducted in which the inside surface of the pultruded planks was treated with epoxy bonded aggregates of two different types; gravel and sand. Simply supported concrete beams with no internal reinforcement were fabricated using the pultruded plank as a form.
The beams were 8 in (200 mm) wide and 7 in (187 mm) deep to simulate the proposed deck depth. Two different lengths, 44 in (1.09 m) and 72 in (1.83 m), were tested in order to investigate shear dominated failure (short beams) and bending dominated failure (long beams). In addition, two control beams were tested; one with no bond treatment on the FRP planks and one reinforced with steel reinforcing bars that did not use a pultruded plank.

Results of the Testing

Selected results of the short beam tests are described briefly in what follows. The simply supported span for this series closely matched the span of the pultruded FRP plank in the actual bridge. Fig. 4 shows the crack pattern at failure of the beam that had no bond treatment while Fig. 5 shows the crack pattern at failure for a beam that had a sand aggregate bonded to the inner surface prior to the concrete casting. Fig. 6 shows the load-deflection plots for the bond treated (1-3) and the untreated (C1) beams.

From the crack pattern shown Fig. 4 it can be seen that the beam with the bond treatment between the FRP plank and the concrete developed significant shear force transfer at the plank/concrete interface which led to the beam failing in shear with multiple flexural cracks. On the other hand the beam without the bond treatment failed in flexure with one large cracked developing at the center of the beam, which is undesirable. From the data shown in Fig. 6 it is seen that the bond treated beams (1-3) develop much higher loads than the untreated beam and that the behavior of these beams is linear after concrete cracking until the ultimate shear failure.
Based on this key result, the pultruded FRP plank was determined to be suitable for use as a permanent form and was able to control the longitudinal cracking in the hardened deck. Further details of the beam testing and additional results for the long beams are provided in Bank et al. (2007).

**Bridge Construction with the FRP forms**

After the girders were placed, steel tie rods were inserted through the webs and tightened as shown in Fig. 7. Thereafter, the pultruded planks were placed on the girder flanges in recesses specifically cast into the beams for this purpose, as shown in Fig. 8. To prevent movement of the pultruded forms and to prevent any seepage of the concrete under the forms during the concrete casting a bead of construction adhesive was applied under the bearing edge of the pultruded plank as shown in Fig. 8. Notice the aggregate bonded to the inside of the FRP planks. After the FRP planks were all placed the deck was poured as shown in Fig. 9. Notice that there is no continuous reinforcement in the deck and that the construction workers are standing on the FRP planks while finishing the concrete.

**75 mm HOLLOW HYBRID SYSTEM**

**Background**
The 75 mm hybrid system was developed to be used in light weight FRP or metallic bridges or platforms in place of conventional timber decking (nominal 3 x 12 in (75 by 300 mm) planks). Fig. 13 shows a view of the timber decking on a typical pultruded FRP bridge.

Solid timber decking for FRP bridges is becoming increasingly expensive, is subject to deterioration due to exposure to the elements, and can only be produced in limited width individual pieces (8 or 12 inches (200 or 300 mm)). A hybrid decking product made of durable FRP and cementitious materials can be produced in large panel widths (e.g., 4 - 6 ft (1.2 – 1.8 m)) and may be a viable replacement for timber in certain situations provided it can deliver equivalent structural performance at similar cost and weight.

**Description of the Panels Tested**

To investigate this hypothesis a pilot study was conducted at the University of Wisconsin (Bindrich, 2007). Two different types of cementitious compression flanges were investigated: (1) A structural cement board panel called FORTACRETE® recently developed by US Gypsum (www.fortacrete.com), and, (2) a thin cast-in-place conventional concrete panel. The cement board panel was attached to the ribs of the pultruded plank in one of two ways: (1) bonding with an epoxy resin or (2) fastened with self-tapping or drywall screws. (The Fortacrete panel is capable of being nailed or screwed like a plywood panel.) The cast-in-place concrete was attached to the pultruded plank by casting a 1 in (25 mm) layer of concrete in a rectangular form,
applying epoxy adhesive to the tops of the ribs and pushing the pultruded plank into the wet concrete about ¼ inch. Fig. 10 shows schematics of the hybrid panels.

The fabricated hybrid panels were 72 in (1.8 m) long. In addition to the hybrid panels tested three other tests were conducted. The stand-alone pultruded plank with the ribs up or down and a timber decking plank were tested. Details of the specimens, their weights, unit weights, and estimated material costs are provided in Table 1. The cost for the FRP pultruded plank used in this study was $5.50/ft² (41.87 €/m²), the Fortacrete Cement Board $3.25/ft² (24.75 €/m²), the concrete $90/yd³ (49 €/m³). Mechanical fastener costs were $5.00 (3.54 €) for Specimen 2 9 (75 fasteners) and $9.15 (6.47 €) for Specimen No. 3 (270 fasteners). The cost of the epoxy used for Specimen No. 1 and labor costs to manufacturing the specimens were not included in the cost estimates.

**Testing and Results**

The hybrid panels were tested in three-point bending over a span of 66 in (1.65m). This is the similar to the span used in FRP pedestrian bridges. The results of the testing are shown in Table 2 and in Figs. 11 and 12. Fig. 11 shows the load deflection results of the panels and Fig. 12 shows the load strain results (where strain gage data was available). Table 2 provides the actual failure loads, normalized failure loads, the deflection at failure and the normalized stiffness and moment capacity of the different panels. More details on the testing can be found in (Bindrich, 2007).
Failure Modes

The 75 mm hybrid panels failed in a number of different modes. The epoxy bonded cement board failed suddenly due to shear at the interface between the tops of the ribs and the board. The failure plane was in the cement board as seen in Fig. 13. When the cement board was fastened to the FRP plank with sparsely distributed screws (Specimen No. 2) the failure mode was pseudo-ductile with the screws either rotating or shearing at the interface. The non-linear load deflection curve for this specimen, seen in Fig. 11, is noteworthy as this implies that such panels can be designed to have a ductile response depending on the number of screws used. Using an estimated shear capacity ($N_{\text{screw}}$) of 800 pounds (3556 N) per screw, the maximum allowable spacing for the fasteners used in this specimen is predicted to be 3.9 inches (98 mm) from the equation, $s_{\text{max}} = \frac{N_{\text{screw}} I}{V_{\text{exp}} Q}$. This is close to the 3 inches (75 mm) used and hence making the failure mode reasonable.

When the screws were closely spaced at 1 in (25 mm) o.c. (Specimen No. 3) the panel failed due to crushing of the cement board without any interface failure. The strain in the cement board reached 3,200 $\mu$ε indicating good mobilization of the compression flange. (According to the Fortacrete specifications (Fortacrete, 2009) the material has a compressive strength of 2,500 psi (17 MPa) and a flexural modulus of elasticity of 600 ksi (4 GPa). This implies a compressive failure strain of 4,166 $\mu$ε if linear behavior of the Fortacrete panel is assumed.) According to the specifications provided by Rock-On, the mechanical fasteners used in Specimen No. 3 had a shear capacity of 1000 lbs (4450 N) per fastener. The maximum spacing of the mechanical
fasteners could be as much as 3.3 in (86 mm) for flexural failure. Failure of the mechanically fastened cement board panel (Specimen No. 3) is shown in Fig. 14.

The hybrid panels with the cast-in-place concrete compression flanges (Specimen Nos. 4 and 5) both failed at the interface between the concrete and the FRP due to dedonding failure in the concrete layer above the ribs of the pultruded plank as shown in Fig. 15 (Recall that the FRP plank is partially embedded in the concrete as shown in Fig. 10). The compressive strain in the concrete only reached 1,400 and 1,000 $\mu$e, respectively, indicating that the concrete was not fully utilized in these specimens. Further testing needs to be conducted to optimize this type of specimen since it appears to be the most cost competitive with the timber plank (see Table 1.)

Shear strength calculations using a transformed section and $\tau = \frac{VQ}{It}$ found that the concrete/FRP interface reached a shear strength of $2.9\sqrt{f'_c}$ and $2.6\sqrt{f'_c}$, respectively, in the two specimens tested. Flexural strength calculations indicate that these specimens could reach loads up to 6,000 lbs with the given test arrangement, 1.8 – 2.2 times the loads achieved in this study. Use of a fiber reinforced concrete (FRC) flange and possible additional mechanical anchorage between the ribs of the plank need to be considered to make this a more structurally feasible option.

The stand alone pultruded planks failed due to buckling of the ribs (Specimen No. 6) and tensile rupture of the ribs (Specimen No. 7), respectively. The strains at failure in Specimen No. 6 were -7,180 and 2,090 $\mu$e and in Specimen No. 7 were -4,750 and 12,730 $\mu$e, which are compatible with the failure modes observed. The buckling failure of Specimen No. 6 is shown in
Fig. 16 while the tensile failure of Specimen No. 7 is shown in Fig. 17. The timber plank failed in a typical flexural tensile mode as seen in Fig. 18.

Both the load carrying capacity and the stiffness of Specimen No. 6, and the stiffness of Specimen No. 7, are insufficient for pedestrian bridge loading which is typically taken as 60 – 100 lb/ft$^2$. (2873 – 4788 N/m$^2$) This demonstrates the need to increase the capacity for the existing planks as considered in this study. Additionally the upper surface of the plank when used in the regular orientation (as in Specimen No. 7) is often slippery (even with the grit) and does not give a similar feel to a timber plank. The cementitious compression flange in the hybrid panel should provide a more familiar sensation for walkers on pedestrian bridges or platforms.

**Recommendations**

From the result of the testing conducted it appears that a 75 mm hybrid FRP panel consisting of a pultruded plank and a cementitious compression flange is structurally viable and may be an economically feasible substitute for timber planks currently used for pedestrian bridges and walkways. The hybrid panels have advantages with respect to larger possible sizes than timber planks (although only 16 in (400 mm) wide panels were tested in this study wider panels can be made), user-comfort relative to FRP only planks, potential longer-term durability relative to timber planks, and the ability to substitute for increasing scarce large (in this case, wide) timber members. Further testing of the cast-in-place concrete option using FRC and/or small shear-studs; structural tests of variable mechanical fastener spacing and corresponding
ductility and strength for the cement board hybrids; long-term durability testing (especially of the
cement board hybrids); as well as structural tests on wide panels for punching shear capacity
should be conducted.

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is acknowledged.

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<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Description</th>
<th>Wt lb (kg)</th>
<th>Unit Wt lb/ft² (kg/m²)</th>
<th>Est. Cost $/ft² (€/m²)</th>
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<tr>
<td>1</td>
<td>Cement board and FRP plank (epoxy bonded)</td>
<td>56 (25)</td>
<td>6.9 (33.7)</td>
<td>8.75 (66.64)</td>
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<td>2</td>
<td>Cement board and FRP plank (self-tapping screws at 3 in o.c.)</td>
<td>55 (25)</td>
<td>6.7 (32.7)</td>
<td>9.50 (72.35)</td>
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<td>3</td>
<td>Cement board and FRP plank (drywall screws at 1 in o.c.)</td>
<td>56 (25)</td>
<td>6.9 (33.7)</td>
<td>10.00 (76.16)</td>
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<td>4</td>
<td>Concrete (3/8&quot; coarse aggregate size) and FRP plank</td>
<td>116 (53)</td>
<td>14.2 (69.3)</td>
<td>5.75 (43.79)</td>
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<tr>
<td>5</td>
<td>Concrete (3/8&quot; coarse aggregate size) and FRP plank</td>
<td>107 (49)</td>
<td>13.1 (64.0)</td>
<td>5.75 (43.79)</td>
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<tr>
<td>6</td>
<td>FRP plank ribs up</td>
<td>19 (9)</td>
<td>2.3 (11.2)</td>
<td>5.50 (41.89)</td>
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<tr>
<td>7</td>
<td>FRP plank ribs down</td>
<td>19 (9)</td>
<td>2.3 (11.2)</td>
<td>5.50 (41.89)</td>
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<td>8</td>
<td>Timber (nom. 3 x 12 in (2 ½ x 11 3/16 in actual) select grade Douglas Fir)</td>
<td>40 (18)</td>
<td>6.5 (31.7)</td>
<td>4.50 (34.27)</td>
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<td>Specimen No.</td>
<td>Max Load lb (N)</td>
<td>Max Unit Load lb/ft (N/m)</td>
<td>Max Defl. in (mm)</td>
<td>Unit Stiffness kip-in²/in (kN-m²/m)</td>
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Figure 6
Figure 11