Life-Cycle Costs of Fiber-Reinforced-Polymer Bridge Decks

By Mark A. Ehlen[1]

Abstract: Fiber-reinforced-polymer (FRP) composites are currently being developed and used in bridge decks. This report examines the life-cycle cost-effectiveness of three FRP bridge decks, using a life-cycle cost method specifically tailored for comparing new materials with conventional ones. The method includes a cost classification scheme for capturing all project-related costs and for comparing the cost advantages and disadvantages of different materials. The uncertainty of new-material costs is assessed using the Monte Carlo simulations. Analysis indicates that one of the FRP decks is life-cycle cost-effective for a particular class of bridges and traffic levels.

INTRODUCTION

Most highway bridge decks are made of steel-reinforced concrete. The cost of maintaining these decks and other parts of bridges is staggering, approximately $90 billion/year (Dunker and Rabbat 1993). Tight budgets at the county, state, and federal levels put pressure on transportation agencies to find new construction materials that make bridges cost less to build, maintain, and replace. Reducing the life-cycle costs (LCCs) of bridges reduces the cost burden placed on transportation budgets and ultimately on taxpayers.

There are new, viable bridge deck materials, some of which may be stronger, more durable, and result in lower LCCs for bridges. Candidate materials include fiber-reinforced-polymer (FRP) composites, high-performance concrete, high-performance steel, and new aluminum shapes. Can these new materials perform the same function as conventional steel-reinforced concrete but at a lower LCC? This article examines the life-cycle cost-effectiveness of three FRP composite bridge decks as compared with conventional reinforced concrete.

Using a LCC method consistent with ASTM E 917 for measuring LCCs, an estimation and comparison is made of the LCCs to build, maintain, and eventually dispose of four geometrically identical bridge decks: one made of conventional reinforced concrete and three made from different FRP composites. At the core of the LCC method is a cost classification scheme that allows the analyst to compare the advantages and disadvantages of each material in economic terms. Sensitivity analysis is then used to measure how LCCs vary with the amount of bridge traffic and conclude with Monte Carlo simulations of uncertain bridge costs that generate cumulative probability distributions of LLCs.

The LCC method and the FRP study are described in Ehlen (1997), which gives a comprehensive treatment of the method but only a summary of the FRP study. In contrast, this paper briefly describes the method but gives a comprehensive description of the FRP analysis. Additionally, this paper uses the writer's bridge life-cycle costing software BridgeLCC (Ehlen 1998), to perform all cost calculations as well as the Monte Carlo simulations not previously reported in Ehlen (1997) and Ehlen and Marshall (1996).

FRP COMPOSITE BRIDGE DECKS

Fig. 1 shows the three FRP bridge decks alongside a reinforced-concrete bridge deck (these are schematic views and not to scale). The thickness of the decks range from 22 cm (8.5 in.) to 34 cm (13 in.). The cores of the Seeman composite resin infusion molding process (SCRIMP) and pultruded-plank (PP) decks span between the bridge stringers and thus run perpendicular to the flow of on-bridge traffic.

The conventional-concrete bridge deck used in our analysis is 22 cm (8.5 in.) thick and made of 21 MPa (3,000 psi) concrete. Reinforcing steel runs both parallel and perpendicular to traffic flow. The deck is constructed by installing formwork between the beams and along the outer beams' edges, laying the reinforcing steel, pouring and curing the concrete deck, stripping the formwork, and then installing the center median and guardrails.

The SCRIMP FRP deck is fabricated with a 9-layer top plate of stitch-bonded e-glass, a 5-layer e-glass trapezoidal inner sandwich, and a 13-layer bottom plate of stitch-bonded fiberglass. The voids between trapezoids and the top and bottom layers are filled with foam to aid in the fabric setting and resin transfer process. Once the top, bottom, and sides are formed, liquid vinyl ester is pulled through the fabric using vacuum pressure. The final deck is 22 cm (8.5 in.) thick and weighs about one-sixth as much as a comparable concrete deck. On site, the beams are prepped for deck placement by first applying an elastomeric bearing along the beams' top edges to prevent excessive localized loads at beam-deck connections. The SCRIMP deck units are attached to the beams with shear pins and attached to one another with long rods running perpendicular to the direction of on-bridge traffic. Three-rail steel guardrails are then fastened along both edges and a concrete center median is installed. Finally, a 2 cm (0.75 in.) polymer-concrete road surface is applied to the SCRIMP surface.

The wood-core (WC) FRP deck is composed of 5.1 cm (2 in.) diameter by 30 cm (12 in.) long vertical Asian structural bamboo sections, which are bonded together with resin, encased in 1.9 cm (0.75 in.) top and bottom fiberglass layers. Fiberglass fabric is soaked in vinyl ester and then applied to the top, bottom, and sides. Each decking section is 2.4 m (8 ft.) wide by 18.3 m (60 ft) long. The left edge of each 2.4 m (8 ft) wide strip is stepped so that adjoining deck sections overlap; the sections are bonded at this overlap, and the seam is sanded before applying a 1.9 cm (0.75 in.) polymer-concrete wear surface. The decking is anchored to the beams, and then the metal barriers, center median, and polymer concrete are constructed. The beams are made larger to account for the lack of composite action between the deck and beams.

The PP deck is fabricated using the FRP pultrusion process. To make the planks, fiberglass strand and fabric are wetted with vinyl ester and pulled through a heated die. Long key strips, shown in Fig. 1, allow three planks to be joined, making a single 61 cm (2 ft) wide plank. The planks are installed on the bridge stringers in a similar fashion as that of the SCRIMP FRP deck. Similar to the WC FRP deck, the beams are made larger to account for the lack of composite action between the deck and beams. A three-rail metal guard barrier is installed

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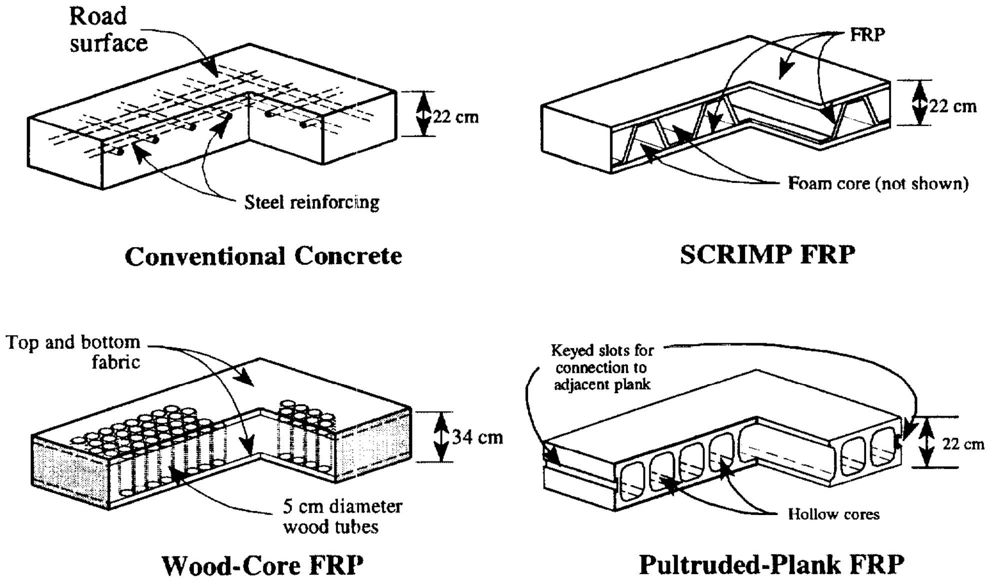

FIG. 1. Conventional-Concrete Bridge Deck and Three FRP Bridge Decks

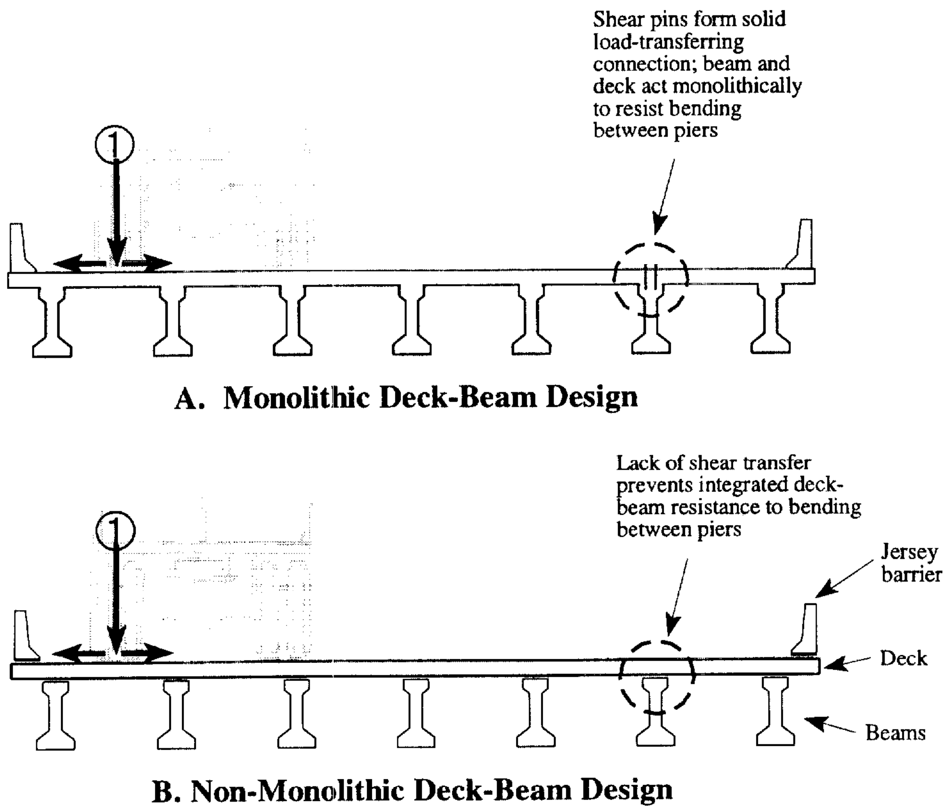

FIG. 2. Comparison of Monolithic Deck-Beam and Nonmonolithic Deck Beam Designs

along both sides of the deck, a concrete center median poured and finished, and polymer-concrete asphalt laid as the final road surface.

An FRP composite bridge deck affects the LCC not only by changing deck costs but also by changing the design and cost of the rest of the bridge. In general, the best design is the one that meets or exceeds the performance requirements of the project at the lowest LLC.

FRP composites affect deck costs. Each of the three FRP decks has large cavities in the middle, taking advantage of the material's high strength and low modulus by concentrating the deck's structural function in the top and bottom layers of fabric. All three are fabricated off-site and in sections. Lightness, precision assembly, and modularity reduce equipment costs, on-site labor, material expense, and construction time, the latter of which reduces the cost of delays experienced by automobile drivers on and under the bridge. In addition, a durable FRP deck (e.g., one that has been designed to reduce water penetration or UV radiation) will last longer, decreasing repair and replacement costs.

FRP composites also affect the costs of bridge components other than the deck. A light FRP deck imposes a lower dead load on the bridge substructure, allowing for smaller, lower-cost beams and piers. However, an FRP deck may not be strong enough to act in concert with the beams to resist bending in the spans between the piers. In this case, the bridge may have to be designed with larger beams (to prevent excessive bending and loading) and larger diaphragms (to prevent lateral-torsional buckling of the main girders); both of these increase bridge costs. Fig. 2 illustrates the impact of a less-strong deck on overall bridge design and cost.

A typical bridge deck has two primary structural functions. The first function is to transfer loads that occur between the beams to the beams themselves (indicated by ① in Fig. 2). The second deck function is to act in a combined manner with the beams to resist bending in the spans between supports.

The monolithic deck-beam design is a superior design for concrete decks as the combined deck-beam assembly can carry more load than a nonmonolithic assembly of the same size (i.e., the resisting moment of the combined deck-beam is greater than the sum of resisting moments of the separated deck and beams). However, the monolithic design may not be optimal or technically feasible for a particular FRP deck. An FRP deck in a monolithic deck-beam bridge may experience stresses in the shear pin connections that exceed its allowable stresses (the dotted circles in Fig. 2 indicate the pin locations). In this case, the deck's primary structural function is to transfer between-beam loads to the beams themselves (① in Fig. 2). The beams must then be larger (and more costly) to offset the reduced between-support carrying capacity of the deck.

The reinforced-concrete and SCRIMP FRP bridges have monolithic deck-beam designs. The WC and PP bridges, on the other hand, have nonmonolithic deck-beam designs with larger, more costly beams. These larger beams correct for the lower resisting moment.

LCC METHOD FOR COMPARING NEW AND EXISTING MATERIALS

An LCC method is used that can compare in economic terms the advantages of new and existing materials. The method calculates and compares the LCCs of a typical structure, such as a bridge deck, made from competing-alternative materials. Each deck is, to the extent possible, equal in that it satisfies the structure's minimum performance requirements such as minimum loads, maximum span deflections between supports, and minimum service life. The steps in the LCC method are as follows:

1. Define the project objective and performance-based requirements.
2. Identify the alternatives that satisfy the project objective and performance requirements.
3. Establish the basic assumptions for the analysis that apply to all alternatives.
4. Identify, classify, and estimate all costs that occur over the life-cycle.
5. Compute the LCC of each alternative.
6. Perform sensitivity analyses.
7. Compare the alternatives' LCCs.
8. Consider other project effects.
9. Select the best alternative.

For our FRP deck analysis, the project objective is to construct, maintain, and eventually dispose of a bridge deck. The overall bridge is 16.8 m (55 ft) wide and has two 26 m (86 ft) main spans and two 9.8 m (32 ft) secondary spans, each composed of seven precast concrete girders. The bridge carries two lanes of secondary-road traffic over four lanes of the interstate highway. The performance-based requirements of the deck are that it be able to carry HS20 loads, that it satisfies L/800 span deflection requirements, and that it last a minimum of 40 years. [Although this was the requirement of the North Carolina Department of Transportation (NCDOT), the general AASHTO requirement is 75 years.] The alternatives that satisfy these requirements are a base-case conventional reinforced-concrete deck and three alternative FRP decks, all shown in Fig. 1. Steps 3–9 calculate the component costs of each alternative, estimate how sensitive the total LCC of each alternative is to changes in component costs, and select the cost-effective construction material. The cost-effective deck is the one that meets the performance requirements of the overall bridge project and has the lowest LLC.

Classifying Costs of New-Material Projects

The LCC of each alternative deck is computed as the sum of individual project cost items, each cost discounted to base-year, present-value dollars. Fig. 3 illustrates how individual project costs are classified. The project LCC is the sum of all project costs. This total is first divided into agency, user, and third-party costs, representing a "Level 1" classification of costs by who pays the cost. Each of these Level 1 groups is then divided into construction; operation, maintenance, and re-

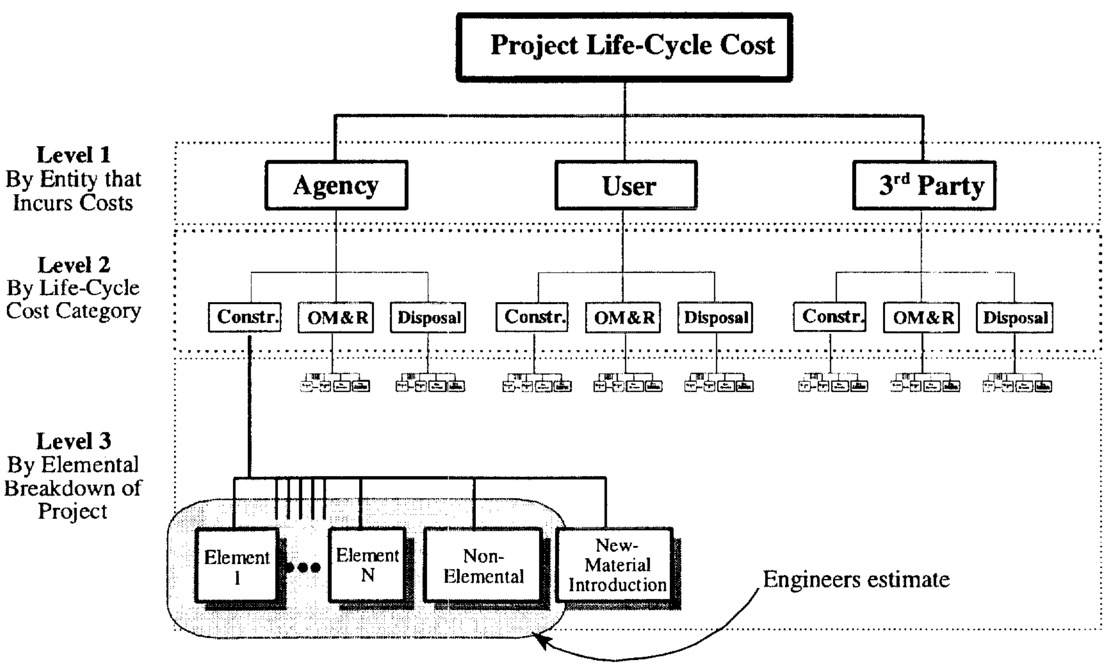

FIG. 3. Classification of Project LCCs

pair (OM&R); and disposal costs, representing a "Level 2" classification according to the period in the life cycle. Finally, each of these life-cycle-period groups is divided into elemental, nonelemental, and new-material introduction groups, representing a "Level 3" classification according to which component generates the cost.

This hierarchical grouping of costs is designed to ensure that all project costs are accounted for, including costs to drivers on the highway and costs of using a bridge material for the first time. The classification also allows designers to compare each material's cost advantages by comparing these cost groups across materials. For example, a designer can compare the engineers' estimates of initial construction costs, which is commonly required in a state department of transportation (DOT) (the Level 3 blocks that constitute an engineer's estimate are in the round-cornered, shaded box at the bottom of Fig. 3).

To be specific, the classification defines each cost by three characteristics:

1. What individuals or entities incur the cost (Level 1).
2. When in the life cycle the cost occurs (Level 2).
3. What component or element of the project generates the cost (Level 3).

There are three types of Level 1 cost: agency (such as a state DOT), user (such as drivers on and under the bridge), and third-party (those who incur costs due to bridge activity but are not direct users of the bridge). Examples of third-party costs are lost business revenues for establishments whose customers are blocked by project activity and environmental damage and costs that result from toxic runoff.

Level 2 then tags each cost to one of three periods in the life-cycle of a bridge: construction, OM&R, or disposal. Finally, Level 3 assigns each cost to a project component: Elemental (such as a beam or pier), nonelemental (such as overhead or profit), or new-material introduction (such as scale-model load testing or nondestructive evaluation over time). A DOT will typically divide elemental costs into specific structure elements such as (1) deck; (2) superstructure; (3) substructure; and (4) miscellaneous components.

New-Material Introduction Costs

FRP composites introduce project costs not experienced with a commonly used material. For example, an engineer may want to test or evaluate a new material. These new-material activities include full-scale model testing and other laboratory tests; demonstration projects; the hiring of consultants and research institutions during the evaluation process; the training of inspection, maintenance, and repair crews in the use of the new material; nondestructive evaluation of the new-material structure; and additional material testing for government acceptance.

In the short run (i.e., during the course of the first few projects to use the new material), the costs of new-material introduction activities are true project costs. They are carried out to validate the material's use in that specific project. In the long run (i.e., after repeated applications of that material in many future projects), these costs lessen as the material is widely accepted in design and it approaches mainstream use. Level 3 has a separate category for new-material introduction costs so that the analyst can subtract these costs and estimate the ultimate LCC of the material after it has been accepted into practice.

LCC CALCULATIONS FOR BRIDGE DECKS

Sources of Cost Data

Private industry, universities, and government agencies provided cost data on the four bridge deck alternatives [for tables of these individual costs, see Ehlen and Marshall (1996)]. These costs were then grouped using the cost classification scheme. Concrete-deck cost estimates were obtained from NCDOT bridge engineers, transportation engineers, and maintenance personnel along with general contractors and concrete deck subcontractors. FRP composite costs were obtained from FRP designers, fabricators, state DOTs currently considering FRP decks, DOTs currently using FRPs, and university research groups testing FRP scale-model structures.

User costs data was obtained from the NCDOT transportation engineering division. There was no indication of third-party costs for this bridge. The bridge is in a remote location, not surrounded by businesses, residences, or environmental zones; construction activity is not likely to affect anyone other than drivers.

LCC Formulas

Each alternative's set of costs was first converted to present value dollars and then grouped using the cost classification scheme. Eq. (1) illustrates how future costs are converted to present value dollars and summed to yield LCC

$$\mathrm{LCC} = \sum_{t=0}^{T} \frac{C_t}{(1 + d)^t} \qquad (1)$$

where C_t = sum of all costs incurred at time t; d = real discount rate for converting time t costs; and T = number of time periods in the study period. The discount rate d was obtained from Office of Management and Budget Circular No. A-94 (*Guidelines* 1992).

The user costs to drivers during road construction are the sum of driver delay costs, vehicle operating costs, and costs due to the increased incidence of automobile accidents. Eqs. (2)–(4) are used to calculate these costs. Driver delay costs and vehicle operating costs are based on the additional time that drivers and vehicles spend in traffic when there is road construction, and accident costs are the costs to drivers caused by the higher probability of highway accidents during bridge construction

$$\text{Driver delay costs} = \left(\frac{L}{S_a} - \frac{L}{S_n}\right) \times \mathrm{ADT} \times N \times w \qquad (2)$$

$$\text{Vehicle operating costs} = \left(\frac{L}{S_a} - \frac{L}{S_n}\right) \times \mathrm{ADT} \times N \times r \qquad (3)$$

$$\text{Accident costs} = L \times \mathrm{ADT} \times N \times (A_a - A_n) \times c_a \qquad (4)$$

where L = length of affected roadway over which cars drive; S_a = traffic speed during bridge work activity; S_n = normal traffic speed; ADT = average daily traffic, measured in number of cars per day; N = number of days of road work; w = hourly time value of drivers; r = hourly vehicle operating cost; c_a = cost per accident; and A_a and A_n = during-construction and normal accident rates per vehicle-kilometer, respectively. Table 1 shows the values of these parameters used in our analysis. They were obtained from the North Carolina and California DOT divisions. Because users costs are sensitive to the traffic volumes on and under the bridge, an alternative set of these parameters is tested in the sensitivity analysis section below.

LCCs of Alternative Bridge Decks

Each alternative deck's LCC is the sum of all costs that are incurred over the life of the deck. Table 2 shows the computed total LCC for each alternative, with cost breakdowns by level categories (the writer's software BridgeLCC was used for all LCC calculations). Note that the sum of all Level 1 (entity that incurs cost) costs equals the sum of all Level 2 (life-cycle) costs which equals the sum of all Level 3 (project component) costs. The costs shown include the FRP new-material intro-

TABLE 1. Project Parameters

Item (1)	Traffic over Bridge Year 1 (2)	Traffic over Bridge Last Year (3)	Traffic under Bridge Year 1 (4)	Traffic under Bridge Last Year (5)
Length of affected roadway (mi) L	1	1	1	1
Average daily traffic (number of cars/day) ADT	30,000	50,000	50,000	80,000
Normal driving speed (mi/h) S_n	45	45	55	55
Driving speed during roadwork (mi/h) S_a	35	35	35	35
Normal accident rate (per million vehicle mi) A_n	1.9	1.9	1.9	1.9
Roadwork accident rate (per million vehicle mi) A_a	2.2	2.2	2.2	2.2
Hourly driver cost (dollars) w	10.73	10.73	10.73	10.73
Hourly vehicle operating cost (dollars) r	8.85	8.85	8.85	8.85
Cost per accident (dollars) c_a	100,000	100,000	100,000	100,000

TABLE 2. LCCs, by Deck Alternative (with New-Material Introduction Costs)

Cost category (1)	Base case (concrete) (dollars) (2)	Alternative Number: 1 (WC) (dollars) (3)	2 (SCRIMP) (dollars) (4)	3 (PP) (dollars) (5)
By entity that incurs cost				
Agency	266,305	345,648	603,328	684,433
User	718,263	545,560	504,901	670,790
Third-party	0	0	0	0
Total Level 1	984,569	891,209	1,108,230	1,355,223
By life-cycle period				
Initial construction	537,320	473,179	779,332	972,490
OM&R	302,349	364,149	304,969	337,123
Disposal	144,899	53,880	23,927	45,610
Total Level 2	984,569	891,209	1,108,230	1,355,223
By project component				
Elemental (deck)	984,569	813,548	1,042,730	1,292,723
Nonelemental	0	0	0	0
New-material introduction	0	77,661	65,500	62,500
Total Level 3	984,569	891,209	1,108,230	1,355,223

duction costs. For example, the LCC of the concrete deck is $984,569 for Levels 1–3 breakdowns of costs.

The WC FRP has the lowest LCC ($891,209), making it the cost-effective bridge deck. Looking at its Level 1 breakdown of costs, the total agency cost is more than the concrete deck ($345,648 versus $266,305) but it has lower total user costs to drivers on the highway ($545,560 versus $718,263). The SCRIMP and PP FRP decks have a similar qualitative relationship to the concrete deck. Comparing the Level 2 costs for the WC and concrete decks, the WC deck has lower initial construction costs ($473,179 versus $537,320), higher OM&R costs ($364,149 versus $302,349), and lower disposal costs ($53,880 versus $144,899). The following sections aid in interpreting the economic advantages and disadvantages of each material.

Agency Costs

Agency costs are observed closely by dividing them into two parts: (1) All agency costs without the new-material introduction costs; and (2) agency new-material introduction costs. The first part includes the costs that the agency can expect to occur after many applications of the new material over the long run. Table 3 shows this first part's Level 2 breakdown of costs. The agency costs are $266,305 for the concrete deck, $267,986 for the WC, $537,828 for the SCRIMP, and $621,933 for the PP deck. Compared to the concrete deck, the WC deck is more costly to install ($252,170), about the same to maintain ($11,932), but is less costly to remove ($3,883).

Bridge design and material costs contribute to the higher initial costs of the FRP decks. The WC and PP decks include a $7,000 surcharge for larger beams (due to their nonmonolithic deck-beam designs) and a $25,000 shipping charge (the WC deck is currently made in only one location nationally; the concrete deck's materials can typically be made close to a construction site). The estimated OM&R work for each of the FRP decks is higher than the concrete deck: in addition to water and UV damage, the FRP may be subject to mechanical wearing of the fabric, requiring repair. North Carolina uses relatively little road salt in the winter; their concrete decks may require less average repair. Disposal costs are significantly lower for the three FRP decks. Although concrete decks are heavy and must be removed with large equipment, the FRP decks require significantly less time and effort.

TABLE 3. Agency LCCs, by Deck Alternative (without New-Material Introduction Costs)

Cost category (1)	Base case (concrete) (dollars) (2)	Alternative Number: 1 (WC) (dollars) (3)	2 (SCRIMP) (dollars) (4)	3 (PP) (dollars) (5)
Agency				
Initial construction	195,000	252,170	506,920	569,670
OM&R	9,733	11,932	23,646	48,316
Disposal	61,571	3,883	7,262	3,946
Total agency	266,305	267,986	537,828	621,933

Our second part of agency costs are the new-material introduction costs. Table 4 shows how these costs range from $62,500 for the PP deck to $77,661 for the WC deck. The WC introduction costs during initial construction are for design consultants ($20,000), laboratory material tests ($30,000), and additional DOT-engineer costs ($8,000). The OM&R introduction costs include $5,000 to develop a nondestructive evaluation plan and additional deck inspections (once a month for the first year plus twice a year for the next 2 years). The other

TABLE 4. Agency LCCs, by Deck Alternative (New-Material Costs Only)

Cost category (1)	Base case (concrete) (dollars) (2)	Alternative Number 1 (WC) (dollars) (3)	2 (SCRIMP) (dollars) (4)	3 (PP) (dollars) (5)
Agency				
Initial construction	0	58,000	60,500	60,500
OM&R	0	19,661	5,000	2,000
Disposal	0	0	0	0
Total agency	0	77,661	65,500	62,500

two FRP decks have similar OM&R introduction activities and costs.

User Costs

User costs are computed as the sum of driver delays, vehicle operating costs, and accidents [(2)–(4)]. Table 5 shows the user costs computed using the project parameters in Table 1. The WC deck has the lowest initial construction costs followed by SCRIMP and then concrete and PP. The WC deck has lower initial construction user costs than the concrete deck as the WC deck is installed by hand in 1 day. This results in fewer traffic delays and accidents. The PP deck takes as long to install as the concrete deck, resulting in no user cost savings over concrete.

The OM&R user costs of each alternative are approximately $300,000. Although the concrete has a lower frequency of repairs than the FRP decks, each repair takes longer. The FRP disposal costs, like the initial construction costs, are lower than concrete disposal due to less time spent dismantling. Finally, there are no new-material introduction user costs associated with introducing the new FRP decks, nor are there third-party costs.

Sensitivity Analysis

The LCCs of each alternative are sensitive to project parameters such as the traffic conditions and the discount rate. In this section the effect of changes in traffic on and under the bridge are considered. All else being equal, bridges in locations with higher traffic levels generate higher user costs. While the WC deck is life-cycle cost-effective for the ADT values in Table 1, it may not be cost-effective in a location with less traffic. To see how sensitive the decks' LCCs are to changes in ADT on and under the bridge, we calculate the same LCCs with a new set of lower ADT values: 5,000 for on-bridge traffic (from year 1 to the last year in the life cycle) and 10,000 for under-bridge traffic (year 1 and last year). The recomputed LCCs are shown in Table 6 (only Levels 1 and 2 are shown). The LCCs are now $373,316 for concrete, $423,188 for WC, $679,378 for SCRIMP, and $787,851 for PP. (The user costs are $107,010 for concrete, $77,540 for WC, $76,049 for SCRIMP, $102,418 for PP.) Although the three FRP decks still have lower user costs than the concrete, these savings are not sufficient to make up for the higher FRP initial construction costs. If the new-material costs are included, the FRP decks are not life-cycle cost-effective in locations with low average daily traffic.

Uncertainty of Costs

The LCCs of each alternative are also sensitive to the certainty with which individual costs are known. For example, a designer may estimate that the cost of installing a conventional bridge deck is between $5 and $6/m and that the cost of installing a new-material deck to be between $1 and $10/m^2. The designer has higher uncertainty about FRP installation costs. Similarly, a designer may estimate that the conventional-concrete deck needs to be resurfaced every 25 years but has little data on what structural deficiencies may appear in the FRP composite deck after 10 years of service life. In this case the designer has higher uncertainty about FRP maintenance costs.

TABLE 5. User LCCs, by Deck Alternative

Cost category (1)	Base case (concrete) (dollars) (2)	Alternative Number 1 (WC) (dollars) (3)	2 (SCRIMP) (dollars) (4)	3 (PP) (dollars) (5)
User				
Initial construction	342,320	163,009	211,912	342,320
OM&R	292,616	332,554	276,323	286,806
Disposal	83,327	49,996	16,665	41,663
Total user	718,263	545,560	504,901	670,790

TABLE 6. Total LCCs, by Deck Alternative (Low-Traffic Bridge Location)

Cost category (1)	Base case (concrete) (dollars) (2)	Alternative Number 1 (WC) (dollars) (3)	2 (SCRIMP) (dollars) (4)	3 (PP) (dollars) (5)
By entity that incurs cost (Level 1)				
Agency	266,305	345,648	603,328	684,433
User	107,010	77,540	76,049	102,418
Third-party	0	0	0	0
Total Level 1	373,316	423,188	679,378	786,851
By life-cycle (Level 2)				
Initial construction	253,923	338,228	603,896	689,093
OM&R	48,961	75,760	66,447	89,381
Disposal	70,431	9,199	9,034	8,376
Total Level 2	373,316	423,188	679,378	786,851

In our analysis, the effect of agency cost uncertainty on the life-cycle cost-effectiveness of the decks is considered, running Monte Carlo simulations with probability distributions of agency unit costs. Each individual agency unit cost in the commonly used concrete deck is modeled as a uniform cost distribution whose average value equals the "best guess" of the costs used above, but whose range is ±10% of that value. For example, if a best guess unit cost were $1/m^2, that cost is now modeled as a probability distribution with an expected value of $1, a lower bound of $1(1 − 0.10) = $0.90, an upper bound of $1(1 + 0.10) = $1.10, and an equal probability of achieving any cost in that range. Next, to reflect a higher uncertainty in FRP costs, the agency costs of each FRP deck are now modeled in a similar fashion as the concrete deck but with a uniform distribution whose range is ±25% of the best guess of each unit cost. The probability distribution of each individual cost is independent of all other costs' distributions. A Monte Carlo simulation was performed with 1,000 random samples to produce the cumulative distributions of agency costs shown in Fig. 4.

Although Table 3 shows that the concrete and WC decks have comparable best guess agency costs ($266,305 versus $267,986, not including the new-material costs), Monte Carlo simulation indicates that cost variability affects whether, in a probability sense, the concrete deck is preferred to the WC deck. Each cumulative density function in Fig. 4 is a locus of points, each point representing the probability that the realized LCC will be less than or equal to that dollar value on the horizontal axis. For example, point A indicates that the SCRIMP FRP deck's agency cost has a 25% probability of being less than or equal to $500,000.

Points B and C indicate that the SCRIMP deck has an 86% probability of being less than or equal to $600,000 whereas

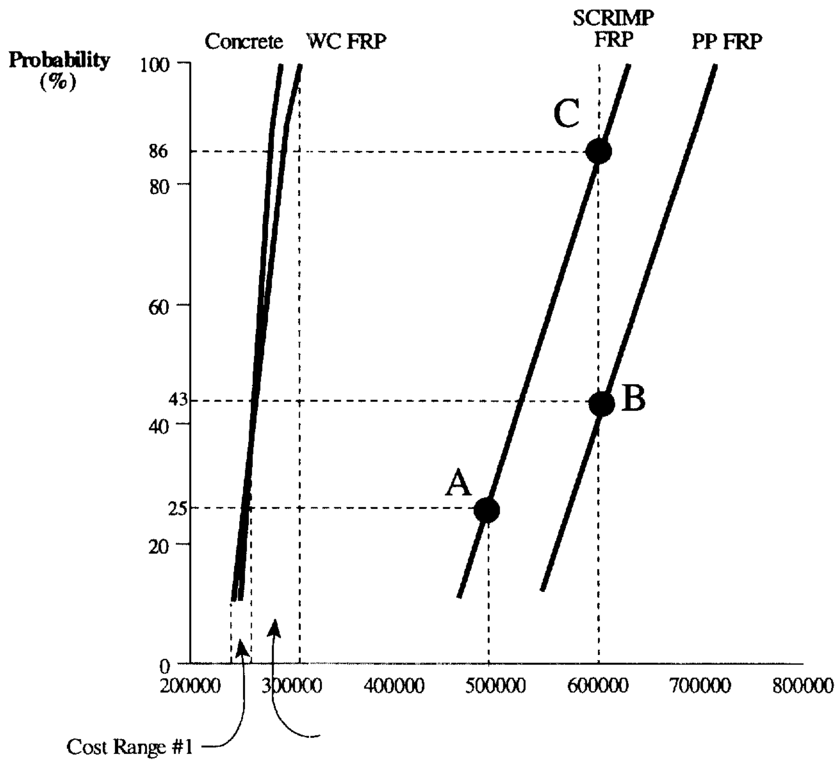

FIG. 4. Cumulative Distributions of Agency Costs, by Deck Alternative (without New-Material Introduction Costs)

the PP deck has a 43% probability of being less than or equal to that same value. Comparing the SCRIMP and PP decks cost-effectiveness in a probabilistic sense, the SCRIMP deck is preferred to the PP deck because, for any given cost value, it has a higher probability of being less than the cost. The WC and concrete decks are both individually preferred to the SCRIMP and PP decks for the same reason.

To see if any deck is the cost-effective deck in a probabilistic sense, the WC and concrete decks are compared. Cost Range #1 (in the lower left-hand corner of Fig. 4) indicates the range of LCCs for which the WC deck is cost-effective (in a probabilistic sense) to the concrete deck, whereas Cost Range #2 indicates the range of LCCs for which the WC deck is cost-effective. Because neither of these two decks is cost-effective across the entire range of possible costs, neither dominates as being cost-effective. Some additional procedures for including risk attitude in project evaluation is required to establish the preferred deck. However, either deck is life-cycle cost-effective when compared to the SCRIMP and PP decks.

Additional sensitivity analyses could be performed to focus on the effects of other cost uncertainties. For example, the new-material maintenance cost uncertainty could also be modeled by listing alternative repair strategies and assigning probabilities and costs to each of them. Instead of estimating a variation in unit maintenance costs, the designer may estimate that there is a 50% probability that the FRP deck will require $5,000 worth of repair every 10 years, and a 50% probability that it will require $20,000 worth of repair every 5 years. Monte Carlo simulations could be run to determine the new range of LCCs.

SUMMARY

Several types of FRP bridge decks are a few of the many new bridge materials being considered for use in highway bridges. These materials may enter mainstream use if they are cost-effective alternatives to conventional materials. This article examines the LCCs of three new FRP bridge decks to determine under what conditions they are a cost-effective alternative to conventional reinforced concrete. These FRP decks were chosen because they were each under consideration by a DOT for highway bridge use; they have wide variation in material and strength characteristics compared to the concrete deck; and they were able to meet the minimum technical requirements of a typical highway overpass.

The WC FRP was a life-cycle cost-effective alternative to conventional reinforced concrete for high-traffic highway overpasses. Although this deck is more costly to construct than a conventional concrete deck (if the new-material introduction costs are included), it is light and can be installed and disposed of by hand, significantly reducing the costs to drivers caused by bridge work. In locations with little traffic, none of the three alternatives had sufficient user costs savings to overcome the relatively large initial costs of their construction. Moreover, if the variability of FRP costs is significantly larger than that for the reinforced concrete, the realized FRP costs can be much higher than their best guess estimates, and structures made from FRPs may not be life-cycle cost-effective in a probabilistic sense.

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