By Dr. Mark Ehlen

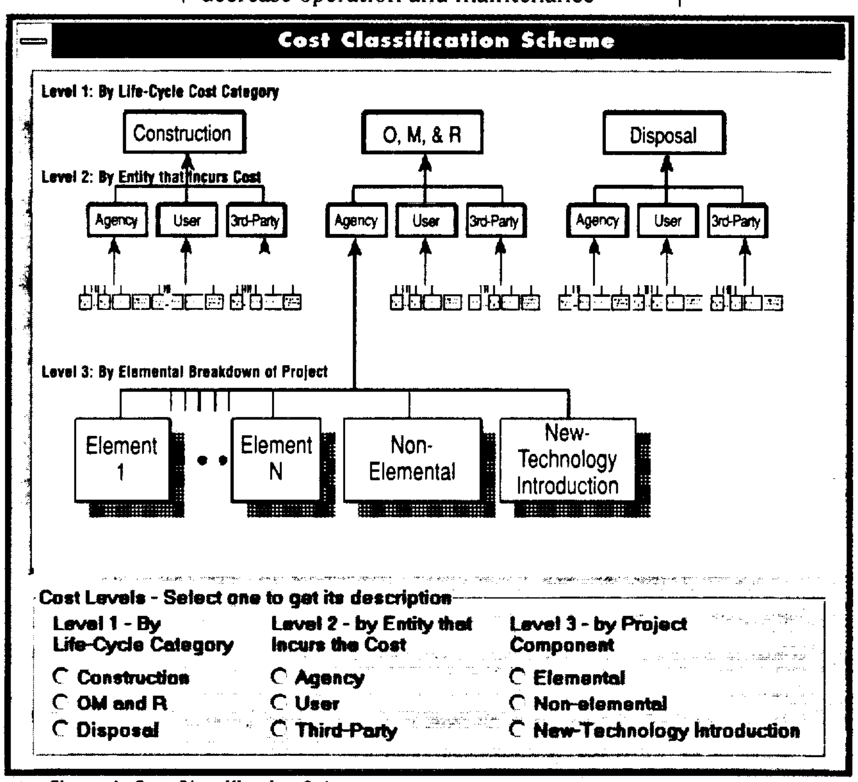
The economics of composites in highway bridges

Fiber-reinforced polymer (FRP) composites are increasingly being specified for structural retrofitting of bridge columns and beams, pedestrian bridges, highway bridge decking, as well as all-composite automobile bridges. And many of these structures are specified by state departments of transportation (DOTs) based on the perceived advantages of composites over conventional construction materials such as steel and reinforced concrete. But there are still a number of experimental or demonstration projects because, to gain significant acceptance by DOTs, such composite structures have to prove that (1) they can technically meet or exceed current loading, safety, and durability requirements set by highway engineers, and (2) that they are cost effective when compared to existing highway construction materials, in particular reinforced concrete and structural steel.

METHODOLOGY AND SOFTWARE DEVELOPED BY NIST EVALUATES LIFE-CYCLE COSTS ASSOCIATED WITH COMPOSITE BUILDING AND CONSTRUCTION MATERIALS

Because the current material cost of a composite structure is typically more than that for a comparable concrete or steel structure, suppliers and fabricators of composites often promote life-cycle costing as the correct way to measure the cost effectiveness of construction materials. Existing Federal mandates already require state agencies to consider life-cycle costs when investing in new highway infrastructure (the Intermodal Surface Transport Efficiency Act [ISTEA] and Executive Order 12893, "Principles of Federal Infrastructure Investment"). Other national mandates, based on partnerships between government and industry, stress the importance of researching and using new materials that increase the durability of structures, decrease operation and maintenance expenses, and decrease project delivery time. The use of FRP composites by state transportation agencies could dramatically increase if their predicted technical and cost advantages can be proven, utilized, and documented.

To fully address these issues, researchers from the Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST) developed a methodology for assessing the life-cycle cost effectiveness of such new-technology materials as composites. Based on ASTM standards for computing life-cycle costs, the assessment method includes a cost classification scheme (Figure 1) that insures that all project-related costs are accounted for, including those costs associated with using a new construction material. This life-cycle cost (LCC) method is illustrated by a case study assessment of the cost effectiveness of FRP bridge decks. User-friendly decision support software called Bridge LCC, also based on this method and currently under development, will allow state bridge engineers and planning officials to compute the LCC of their new and existing highway bridges and to choose construction materials that reduce LCC of building and maintaining their highway infrastructure.



➤ *Figure 1: Cost Classification Scheme*

The life-cycle costs of FRP bridge decking

An important test of any LCC methodology is a case study. Not only does a case study gage the method's usefulness, but for new materials like composites, it determines whether sufficient industry knowledge exists to compute life-cycle costs. Using an overpass currently under construction in rural North Carolina as the case study, we compared the life-cycle costs of three different types of composite bridge decks to that of the reinforced concrete slab specified in the bridge's construction blueprints.

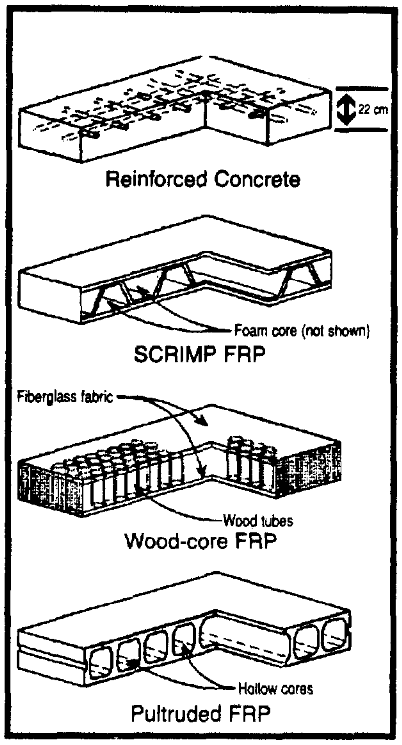
We chose the North Carolina bridge for several reasons.

■ First, it is somewhat typical of overpasses–it carries two lanes of traffic over four lanes of highway, its total length is 216 ft. (71.6 m), and it has an 8-in. (22 cm) reinforced concrete slab monolithically poured over precast, prestressed concrete beams.

■ Second, because it is currently under construction, we were able to obtain accurate data on project costs, project schedules, and during-construction traffic rerouting plans. We chose to compare three FRP bridge decks (instead of just one) to the traditional reinforced-concrete deck because FRP is a new construction material. Design, materials production, and installation methods for reinforced concrete have been developed and refined over the last 100 years, but FRP bridge decks are very new, resulting in a range of different designs. Comparing several FRP designs allows us to see how life-cycle costs vary between these new designs.

The three FRP bridge decks (and the reinforced concrete deck) are shown in Figure 2. The SCRIMP (Seeman Composite Resin Infusion Molding Process) deck is fabricated by positioning E-glass with closed-cell foam and an external mold; once the resin sets, the mold is removed and the foam remains as a permanent, non-structural part of the deck. The Wood-Core deck is fabricated by clustering vertical Asian structural bamboo sections into a rigid sandwich core, covering the top, bottom, and sides with layers of fiberglass, and applying resin. Like the foam core in the SCRIMP deck, the bamboo is a permanent part of the bridge deck. The third FRP deck material is a Pultruded Plank.

The North Carolina bridge had to be partially redesigned before two of the three decks could be used. In most concrete overpass bridges, the concrete deck is designed to work monolithically, with the beams to resist bending between the support columns underneath. This places large compressive loads on the deck, as well as loads caused by shear between the deck and beams. The Wood-Core and Pultruded Plank decks were not designed to carry these loads, but they do not necessarily have to. For these two, the bridge was redesigned with stronger beams so that the deck would not have to help in resisting beam bending. The SCRIMP deck, on the other hand, was designed to have the same structural function as the conventional concrete deck, and thus did not require stronger beams.



➤ ***Figure 2: Alternative deck materials***

The LCC methodology has some important characteristics that allow composites to be evaluated on an equal basis with existing construction materials. The method is project-based, which means that the materials are compared based on the costs to build typical structures, instead of measures such as "dollars per pound of material." The main requirement of the project is that the structure being designed and built from each material must satisfy a set of minimum performance requirements. For example, for each alternative bridge deck material in our case study, the bridge itself must, at a minimum, carry two lanes of NC130 traffic over four lanes of I-17 traffic, be designed for AASHTO HS-20 loads, and its beams must not deflect more than a specified amount. Finally, the cost classification ensures that all project-related costs are accounted for, including costs to drivers on the highway during bridge construction and costs to businesses adjacent to the roadwork that are impacted by bridge activities. The classification is important because it allows the cost analyst to compare the strengths and weaknesses of each material alternative based on the complete set of costs directly attributable to project activities. Our method for computing costs to highway users (user costs) is based on a method used by the California DOT and is similar to methods developed at North Carolina State University for the Federal Highway Administration.

We accumulated the costs of four different bridge decks (the concrete deck and the three FRP decks) over the life of the deck. Using the cost classification scheme as a template, we estimated the costs of construction; operation, maintenance and repair; and disposal of the bridge deck. For each of these three life-cycle categories, we computed the costs to the DOT and to the drivers on the highway during these corresponding phases. We could have also computed the costs to third parties such as the gas station that is near the bridge, but the North Carolina DOT (NCDOT) is redirecting traffic in such a way as to not impact those businesses significantly. Finally, for the DOT and the drivers, we broke down the costs to them into project-element costs (in this case, the bridge deck) and new-technology introduction costs–those costs related to monitoring and evaluating the new-material component of a structure. The cost of introducing composites in the case study included laboratory material tests, predesign project formulation, outside consultants to assist in design, extra construction inspections, and non-destructive evaluation over the structure's life cycle.

The costs of constructing and demolishing the reinforced concrete deck were obtained from the engineer who designed the bridge, the general contractor who was awarded the bridge contract, and discussions with the subcontractor charged with building the deck itself. Operation, Maintenance and Repair figures were obtained from NCDOT maintenance officials. An NCDOT traffic engineer supplied us with their plans to reroute NC130 and I-17 traffic during bridge work, along with current and future estimated daily traffic volumes for the two highways. FRP fabricators supplied us with budget prices for materials, as well as cost estimates and timetables for deck installation, maintenance, repair, and demolition. The Virginia Transportation Research Institute provided recent contract bid prices for the polymer-concrete road surface that is applied to all three FRP decks, along with a timetable for repairs of the polymer concrete.

The study period chosen for the LCC analysis was 40 years (1996 through 2036), based on NCDOT's requirement that the conventional concrete bridge last 40 years, and the composite industry's assessment that the three FRP alternatives should last at least 40 years as well. At the end of the 40 years none of the four deck alternatives was considered to have a residual, salvage value. Costs occurring in the years 1997-2036 were discounted to the base year 1996 at an interest rate of 3.09%. This rate is set by the Office of Management and Budget for federal infrastructure projects and does not include the rate of inflation. Private owners and builders may use a different discount rate, depending on their own time value of money.

Our primary finding from the LCC analysis of the North Carolina overpass was that, when the new-technology introduction costs were included in the project costs of the three FRP alternatives, none of the alternative composite decks was cost-effective compared to the concrete deck specified in the construction drawings. But when these new-material costs were excluded, the Wood-Core FRP deck had the lowest life-cycle cost. Including and excluding these new-technology introduction costs allow the analyst to compare the short-run and long-run life-cycle costs of new materials. Including the costs shows what it costs today (i.e., in the short run) to build and use a structure made of composites. Excluding these costs shows what it will cost over the long run when the material has been tested, verified, and accepted in the field.

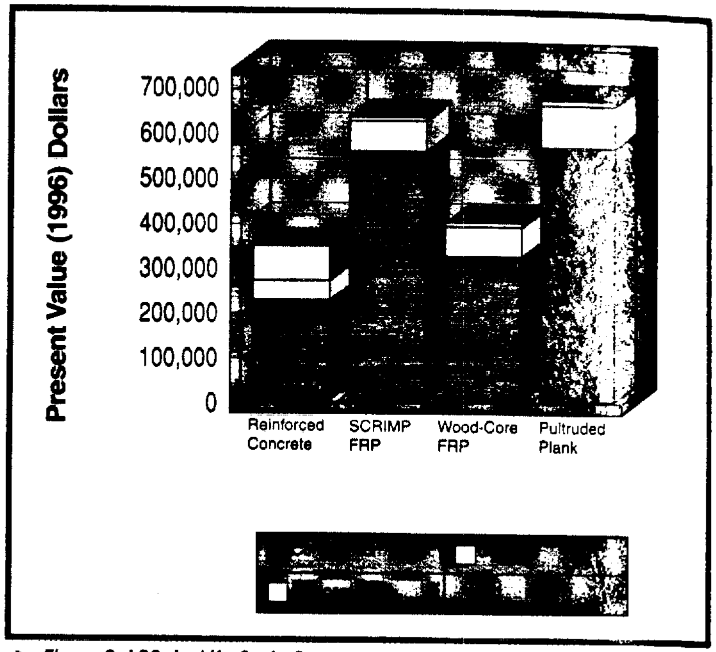
We can use the classification to display some of the economic strengths and weaknesses of FRP bridge decks. Figure 3 shows that although the reinforced concrete has the lowest construction cost (as shown by the purple blocks in the diagram), it has a much larger cost of disposal (the orange blocks). Figure 4 shows that the user costs (the green blocks) of the SCRIMP and Wood-Core FRP decks are less than those for concrete, mostly due to the reduced amount of time that drivers are delayed while the composite decks are installed, repaired, and eventually disposed of. Figure 5 shows the short-run and long-run LCCs of new materials. In the short run, FRPs are not cost effective due to the new-technology material costs (the orange blocks). Once composites are accepted, the new-technology introduction costs disappear; the Wood-Core FRP deck then has the lowest life-cycle cost of the four alternative bridge deck materials.

The road ahead

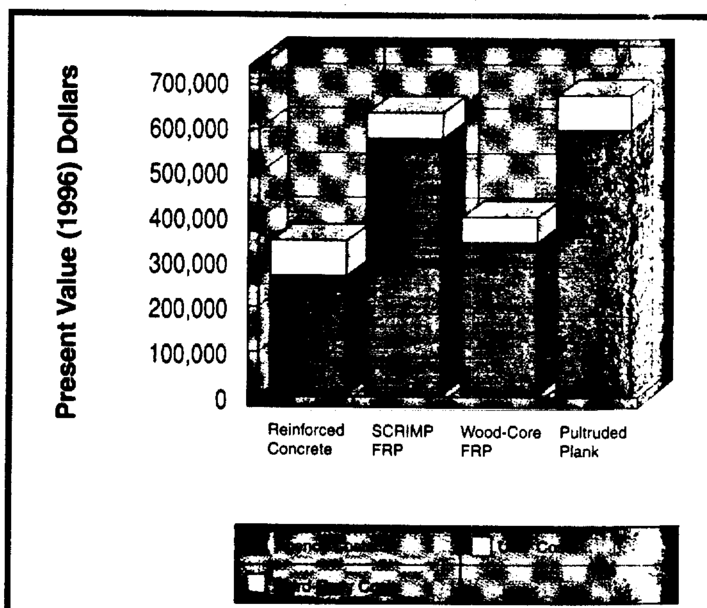
NIST's LCC method lays the groundwork for overcoming the perceived cost barrier by developing an economic means of comparing new materials to conventional construction materials. BridgeLCC, a user-friendly decision support software that uses the LCC method, further speeds the assessment process by providing an automated framework–with supporting technical and economic information–for arriving at intelligent decisions about the construction material that best fits a particular application.

An example of this framework is the case study comparison of three FRP bridge decks to the conventional reinforced concrete deck. The LCC method highlighted at least three important characteristics of FRP decks: (1) Though they may have high costs of construction, they can be cost effective in the long term; (2) They reduce the costs incurred by drivers on the highway–the taxpayers directly paying for the highway system itself; (3) Although the costs of introducing the FRP material–the "new-technology introduction" costs–may not be an insignificant part of total life-cycle cost, these costs dissipate when they are shared over numerous projects and when the material is used over time.

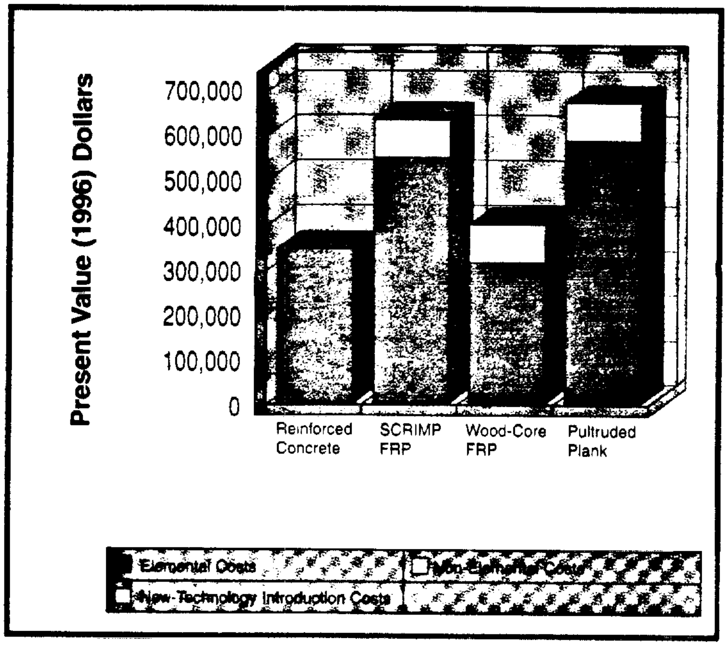
A problem for FRPs (or any other new construction material) is the lack of knowledge regarding how long the material will last; this affects estimates of life-cycle costs. LCC methods can accommodate this uncertainty by using simulation techniques, but research on the durability and serviceability of FRP structures is



➤ ***Figure 3: LCC, by Life-Cycle Category***



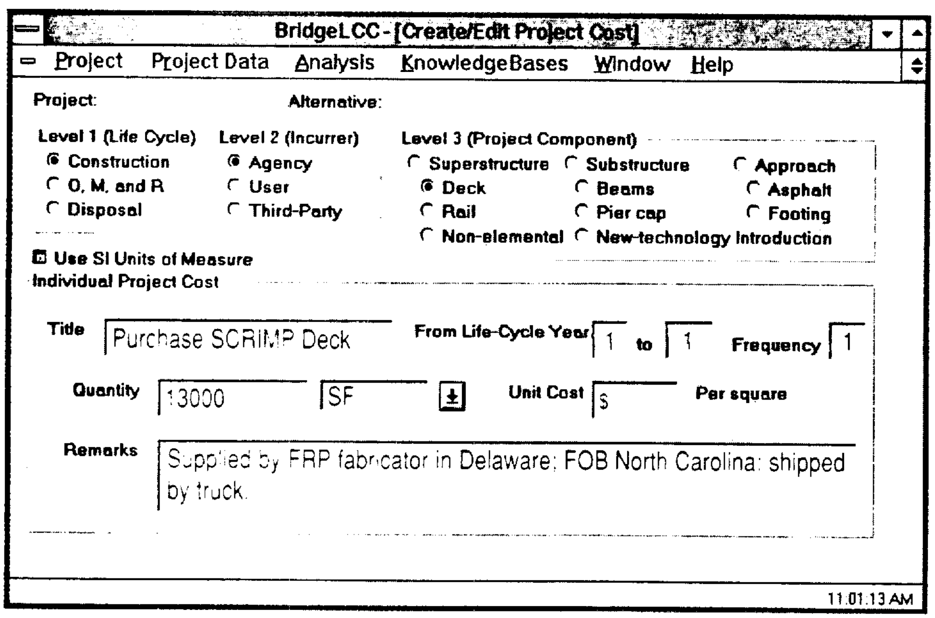
➤ ***Figure 4: LCC, by Entity that Bears the Cost***



➤ *Figure 5: LCC, by Project Cost*

essential. Another factor affecting cost-based decisions is the potentially large change in the market costs of composites. New materials often lack a stable, well-organized, and competitive market of base-material suppliers and fabricators. A composites industry with more designers, fabricators, and installers than today will most likely bring down the material costs of composites. Production costs will likely decrease as fabrication techniques improve and as the scale of production increases.

A larger concern is the lack of adequate state and federal highway funds for building and maintaining the U.S. transportation system. Widespread disrepair of existing highway structures is putting pressure on DOTs to find innovative, cost-effective repair methods and to develop new structures that last longer and require less repair.



➤ *Figure 6: LCC, Project Cost Information*

BridgeLCC: Bringing LCC to state DOTs

We are developing BridgeLCC software to automate cost-collecting processes and import state bridge data, including bridge size and daily traffic statistics, from the PONTIS bridge management system currently licensed to 40 state DOTs. It will also import spreadsheets of such DOT data as engineer's estimates of construction costs, bridge maintenance and repair costs, and cost data from material alternatives that are part of other BridgeLCC project analyses. The software includes detailed project cost information (Figure 6), online help describing the LCC method and cost classification (Figure 1), and graphical summaries of alternative materials' costs (Figures 3 through 5). A state DOT will be able to share electronically BridgeLCC analyses with other DOTs.

Automation of the costing process, however, only lowers one of the two barriers that hinder the use of new materials. The other barrier, the lack of technical information used by engineers to educate themselves with a material, will be addressed with the inclusion of a materials database, part of NIST/BFRL's Computer-Integrated Knowledge System (CIKS). CIKS should include material properties, examples of fabrication techniques, photographs of completed projects using the material, and BridgeLCC analyses of other projects that use the material.

BridgeLCC will also include methods for assessing the uncertainty of costs that result from using a new material. Precise estimates of the construction, operation, maintenance and repair, and disposal costs associated with composites are hard to find. Likewise, estimates of how long an FRP bridge deck will last are less certain than they are for concrete decks. BridgeLCC will allow users to input a distribution of costs for each cost element. For example, the analyst can estimate that the labor cost to install a SCRIMP deck is between $5-10/sq. m. BridgeLCC will then use Monte Carlo simulation techniques to produce a distribution of the total LCC for the material alternative. Uncertainty regarding how many years an FRP bridge deck lasts can be treated in a similar fashion.

A copy of the NIST report, "The Economics of New-Technology Materials: A Case Study of FRP Bridge Decking," can be obtained by writing to Mark Ehlen, Office of Applied Economics, Building 226, Room B226, NIST, Gaithersburg, MD 20899 or e-mail at mark.ehlen@nist.gov. Summary information about the project can also be viewed at http://titan.cbt.nist.gov/proj1029.htm. A beta version of BridgeLCC will be completed by the Fall of 1997.

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