LIFE-CYCLE COSTS OF NEW CONSTRUCTION MATERIALS[a]

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ABSTRACT: New high-performance construction materials are being developed for transportation structures. Economic methods are needed for assessing the life-cycle cost advantages and disadvantages of these new materials relative to conventional materials. This paper provides a step-by-step, project-based approach based on life-cycle costing, minimum performance requirements, and a cost classification scheme that organizes a construction material's life-cycle cost advantages and disadvantages. A case study example of the method analyzes the cost effectiveness of fiber-reinforced-polymer bridge decks relative to reinforced concrete decks.

INTRODUCTION

Highway structures are typically built from two construction materials: steel-reinforced concrete and structural steel. Both materials decay in predictable ways, and bridges and overpasses made from them deteriorate to a level where the structures must be rehabilitated or replaced. The cost of rehabilitating these bridges or replacing them with new ones is staggering, approximately $90 billion a year [Dunker and Rabbatt (1993)]. Declining state and federal highway funds are putting pressure on transportation agencies to find new materials and designs that make bridges cost less to construct and last longer.

High-performance materials are currently being developed for bridges and bridge components. High-performance concrete, high-performance steel, aluminum, fiber-reinforced polymer (FRP) composites, and FRP-reinforced timber are a few of the construction materials being used in innovative ways. They are specified because they often have some qualitative performance advantage over a conventional material. For example, high-performance concrete is significantly stronger and more impervious to road salt intrusion than conventional concrete. FRP composites give designers the flexibility to create unique and light structural shapes which can be installed by hand instead of by crane. Aluminum bridge elements are light and can be recycled. FRP-timber components are light and aesthetically pleasing.

Which, if any, of these "new" construction materials is a better overall alternative to conventional construction materials? Clearly some minimum technical criteria must first be satisfied. What is the material's ultimate strength? How durable is it? And how does it extend or constrain the serviceable life of the overall structure? If the new material meets these technical requirements the final criterion is cost: Which material provides the lowest-cost facility? At least two federal mandates drive this criterion: the Intermodal Surface Transportation Efficiency Act [*Intermodal* (1991)] and Executive Order 12893 [*Federal* (1994)]. They require project planners to consider the costs of a proposed project (such as a bridge) over its entire life span (i.e., its life-cycle costs). Other, cooperative mandates between private industry and government seek to promote new materials that reduce project delivery time, decrease infrastructure operation and maintenance costs, and create structures that last longer; that is, they seek to reduce facilities' life-cycle costs. Together, these technical and cost-minimizing requirements determine the technically sufficient and life-cycle cost-effective material.

Recent life-cycle cost research has focused on general models and methods [Ellis et al. (1995); Chang and Shinozuka (1996)]; the life-cycle cost of existing concrete and steel bridges [Cady and Weyers (1984); Purvis et al. (1992); Gannon et al. (1995); Tam and Stiemer (1996a,b)], of high-performance concrete bridges [Clements (1995)], of timber bridges [Sarisley (1990)], of coatings [Bernecki et al. (1995)], and of repair and retrofit [Hyman and Hughes (1983); Cady (1985); Wipf et al. (1987); Morrow (1987); Markow et al. (1993)]; service life prediction [Cady and Weyers (1992); Purvis et al. (1994)]; and systems for managing networks of bridges [Weissman et al. (1990); Stukhart (1991); Reel and Conte (1993); Thompson (1993)]. Few if any of these studies provide a detailed method for estimating the costs of a structure made from new or nonconventional construction materials. This paper presents such a method.

LIFE-CYCLE COST METHOD FOR NEW CONSTRUCTION MATERIALS

The new-material life-cycle cost method has three important characteristics. First, it is a "project-based" approach; that is, the method computes the life-cycle costs of typical structures such as highway overpasses. Second, the method allows the designer to choose any construction material that satisfies the project's performance requirements. For example, to build a two-lane, two-span overpass, the project planner can specify that each material satisfies a set of minimum performance capabilities, including that the overpass built from it (1) be able to carry AASHTO HS20 loads; (2) not deflect between spans more than a prescribed limit; and (3) last a prescribed minimum number of years. None of the performance requirements assumes or precludes the use of a particular material. The third important characteristic of the method is that it includes a cost classification scheme which allows the bridge planner to compare the intrinsic life-cycle cost advantages and disadvantages of a new material to those of conventional materials. The next four sections describe the method in detail.

Steps for Choosing Cost-Effective Construction Material

Although the new-material life-cycle cost method can be applied in numerous types of analyses [for a list of these types, see Ruegg and Marshall (1990)], it is primarily a tool for comparing new construction materials such as high-performance concrete to conventional materials such as normal-strength reinforced concrete. The life-cycle cost method's steps for comparing and choosing a cost-effective construction material are as follows:

1. Define the project objective and performance-based requirements.

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

In the first step, the project planner defines the specific project, say, the construction of a two-lane overpass. The step specifically caters to comparing new materials and conventional materials on an equal footing (that is, the project is an "overpass," not a "concrete overpass"). Current engineering practice inhibits the use of new materials because designs are often based on codes which prescribe specific construction materials. Step 1 allows the project planner to set minimum project performance requirements such as load-carrying capacity and span deflection. In Step 2, the planner can then select alternative materials that satisfy Step 1's requirements.

In Step 3, the planner estimates those project parameters that are common to all material alternatives such as the estimated traffic flow on and under the bridge, the value of drivers' time when they are delayed by construction work, and the rate at which future costs are discounted to the present. The focus is on project attributes that are not tied to a specific material.

Cost Classification Scheme

Each alternative's costs are estimated in Step 4. Fig. 1 illustrates the method's cost classification scheme, which helps the user compare alternative construction materials. The cost classification insures that all project costs are accounted for by helping to itemize all "project activities." Each project activity occurs at a specific time, occurs on one or more parts of the project, and affects (monetarily) an individual or agency. Each project activity generates a "project cost." The cost classification categorizes each of these costs according to three characteristics: (1) When the cost occurs; (2) what component of the project generates the cost; and (3) what individual or entity incurs the cost. Grouping a project's costs by these characteristics allows the project planner to compare the life-cycle costs of competing materials in useful ways. For example, which material alternative has the highest maintenance and repair cost, the highest first-time-use cost, or the highest cost to drivers on the highway?

Fig. 1 illustrates how the classification is hierarchical: the life-cycle cost of the structure is first divided into construction costs; operation, maintenance, and repair (OM&R) costs; and

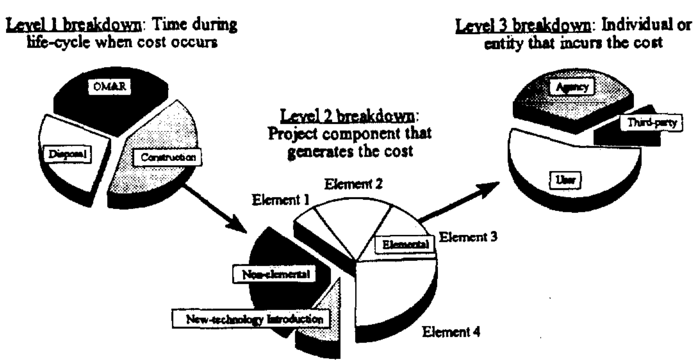

FIG. 1. Grouping Project Costs according to Cost Classification Scheme

disposal costs ("level 1" in Fig. 1). Each of these three components is then divided into cost groups according to where the costs originate ("level 2"): elemental costs (e.g., the superstructure, labeled "element 1"), non-elemental costs such as construction mobilization, or new-technology introduction costs such as nondestructive evaluation of a new-material structure. Each of these project-component costs is then finally divided into groups according to whether an agency, user, or third party pays the cost ("level 3").

The central purpose of the classification is to express the technical advantages and disadvantages of a new material in life-cycle cost terms. The level 1, level 2, and level 3 categories facilitate this technical-to-cost mapping and, wherever possible, do it according to conventional cost estimation techniques. The level 1 categories quantify the technical advantages and disadvantages of a material over a structure's service life using time periods standard in life-cycle cost analysis. The level 2 categories determine which components of a project save or cost more money when constructed of a new material. State departments of transportation (DOTs) often estimate project costs using an elemental classification of the structure. Finally, the level 3 categories insure that a new material's technological impact on all parties is accounted for. Agency costs and user costs are often computed for highway structures; third-party costs account for the remaining individuals who do not use the structure directly but are still affected by project activities.

Separately, each classified cost answers the question: how does each part of the project affect whom, and when? Together, the set of classified life-cycle costs insures that the question of a new material's technical and economic advantages over conventional materials can be answered.

Consider an example: the deck installation cost of a new bridge that is being funded by a state department of transportation. Deck installation occurs during the construction phase and thus is grouped in the "construction" section at level 1. Given that it is a construction cost, it is next categorized according to which project component generates the cost; in this case it is the bridge deck. The specific set of elements used (elements 1–4 in Fig. 1) constitutes an all-inclusive set of project components, an "elemental classification" of the structure. A natural choice of elemental classification for bridges is the classification used by the PONTIS bridge management system [see "AASHTO" (1997)]. The PONTIS bridge classification consists of four elements and nine subelements:

1. Deck/slab
2. Superstructure
3. Substructure
    a. Column or pile extension
    b. Pier wall
    c. Abutment
    d. Submerged pile
    e. Culvert
4. Other
    a. Expansion joint
    b. Bearing
    c. Approach slab
    d. Bridge railing

One all-inclusive set of components is made up of the four main elements: deck/slab, superstructure, substructure, and other. Another equally viable all-inclusive classification includes the first two elements, deck/slab and superstructure, plus the subelements listed for substructure and other. Using either classification, our deck installation cost is classified as a deck/slab elemental cost.

New-Technology Introduction Costs

The last type of level 2, project component costs are new-technology introduction costs. These costs are generated from testing, evaluating, and bringing the new material to accepted, mainstream use. Specific examples of these activities [taken from Rosen and Bennett (1979)] are

- Material- or design-specific laboratory tests
- Outside consulting on design and implementation
- Destructive testing
- Full-scale testing
- Nondestructive evaluation
- Demonstration projects

If the example bridge deck is made of a new material such as FRP composite, then any on-site testing and monitoring costs that occur during installation are classified as new-technology introduction costs. It is important to estimate these costs because they are true project costs.

Isolating these introduction costs allows one to compare the short-run and long-run life-cycle costs of using a new construction material. In the short run, a new construction material creates additional project costs due to additional design, the time spent with fabricators, designers, and material specialists, and the evaluation of the material's performance over the life of the structure. In the long run, however, these introduction costs disappear as the material obtains an accepted design and monitoring protocol similar to that for conventional materials. The new-technology introduction classification facilitates direct comparison of short-run and long-run life-cycle costs. Include these costs for a short-run life-cycle cost comparison of materials, and exclude them for a long-run, accepted-practice comparison.

Given that the example's bridge deck installation cost is classified as a level 1 construction cost and level 2 deck/slab cost, it is lastly classified according to the individual or entity that incurs the cost: (1) The agency that owns/maintains the structure; (2) the users of the structure during project activity; or (3) third-party entities that are not direct agents or users of the project but are affected by the project's activities. The installation cost of the example bridge deck is an agency cost because the state DOT bears the cost. Additional costs to users of the highway (drivers) during installation of the deck would be classified as user costs; examples of user cost formulas are given in Appendix I.

Third-party costs are incurred by individuals who are not direct users of the project but are impacted by project activities. An increasingly important third-party cost is the environmental cost of construction materials [see "Environmental Management" (1996); *Environmental Resource* (1996); Lippiatt (1997); "Working" (1997)]. The third-party category allows not only for inclusion of "downstream" environmental costs such as pollution of wetlands caused by toxic runoff from a specific project, but also "upstream" environmental costs such as pollution resulting from the mining, fabrication, and transport of the construction material. These third-party environmental costs may be large enough to outweigh a particular material's other cost advantages.

Each individual project cost is categorized in the same manner as the example deck installation cost. The classification scheme then allows the planner to compare the material-structure alternatives according to their life-cycle cost advantages and disadvantages. The life-cycle cost of each material-project alternative is computed by summing all project costs that occur over the life-cycle of the project. Eq. (1) describes mathematically the discounting of project costs to their present value and their summation to a single life-cycle cost number.

$$\text{Life-cycle cost} = \sum_{t=0}^{T} \frac{C_t}{(1+d)^t} \quad (1)$$

where C_t = the sum of all costs incurred at time t; d = the discount rate for converting time t costs to time 0; and T = the number of time periods in the study period. The costs C_t are typically denominated in constant dollars (e.g., what they cost in 1997 dollars) and the discount rate is typically the real discount rate, which accounts for inflation. The same discount rate and time period are used for all project alternatives. Public projects are typically mandated to use a specific rate [see Ruegg and Marshall (1990), pp. 142–146], while private projects may specify their own interest rate.

The decision rule for selecting the cost-effective construction material, given that each competing material satisfies the minimum performance requirements of the project, is to choose the one that has the lowest life-cycle cost.

Uncertainties about New-Material Costs

Step 6 of the life-cycle cost method is a fundamental part of assessing new construction materials. The costs and technical performance of new materials are intrinsically uncertain; the method must address this uncertainty. The true costs of constructing, maintaining, and disposing of a new-material structure are less certain than the same costs for commonly used materials. For example, while it may be hypothetically known that the annual cost to repair a conventional reinforced concrete deck is between $2.00 and $2.10 per square meter, a similar FRP composite deck may have estimates of anywhere from $0.50 to $5.00 per square meter. This variability of FRP costs can greatly affect the life-cycle cost of the entire structure. The technical performance of a new material is also uncertain. A new-material structure that has some probability of experiencing premature failure and requiring significant rehabilitation or replacement will have a higher expected life-cycle cost than one that does not fail prematurely. Standard methods of risk analysis and Monte Carlo simulation can be used to compute cumulative distributions of life-cycle cost for each alternative [these methods are outside the scope of this article; see Marshall (1988)].

In Step 7, the cost classification goes to work. The classification allows the analyst to compare the advantages and disadvantages of each material alternative in life-cycle cost terms. Step 8 allows the user to consider other project factors that cannot be quantified; some examples are local architectural conditions that make some materials less aesthetically desirable, and nonquantifiable environmental emissions. Additional tools such as multiattribute decision analysis (MADA) may be required [see *Practice* (1996)]. In Step 9, the life-cycle cost-effective construction material is finally selected.

EXAMPLE OF LIFE-CYCLE COST METHOD: FRP COMPOSITE BRIDGE DECKS

A complete example of this new-material life-cycle cost method is a recent case study comparison of FRP composite bridge decks to conventional reinforced concrete decks [for complete details see Ehlen and Marshall (1996)]. The case-study, "typical" structure was a two-lane, two-span concrete bridge in North Carolina. The bridge's construction drawings called for a conventional 210.9 kg/cm^2 (3 ksi) reinforced concrete deck. Following the steps of the method, the "project" was defined as the construction, maintenance, and eventual disposal of the bridge's deck. The material-independent performance requirements of the bridge deck were that (1) The deck must carry AASHTO HS-20 design loads; (2) deflections between spans must not exceed a maximum amount; and (3) the deck must last 40 years. Three FRP composite deck materials were chosen as the alternative deck materials to the base case reinforced concrete deck.

The costs to build, repair, and eventually dispose of each deck alternative were compiled using the cost classification scheme and the cost estimates received from North Carolina DOT bridge engineers, transportation engineers, and maintenance personnel along with general contractors and concrete deck subcontractors. FRP composite costs were given by FRP composite designers, fabricators, state DOTs currently considering FRP composite use, DOTs currently using FRP composites, and university research groups testing scale models of FRP composite structures. Two of the FRP composite deck designs did not have sufficient strength to help resist deflections in the spans. The depth of the bridge's beams was increased to counter this reduction in deck strength, and an additional charge was placed on the deck installation cost to pay for the larger beams.

Figs. 2–4 compare the life-cycle costs of the reinforced concrete deck and one of the three alternative decks using the classification scheme. The FRP composite pie charts in each figure show the costs to test, design, and inspect the FRP composite deck (i.e., the new-technology introduction costs). From Fig. 2 we can see that, while the FRP composite deck has a higher construction cost ($325,000) than the reinforced concrete ($225,000), its disposal cost ($12,000) is significantly lower ($75,000 for the concrete). The FRP construction costs are higher due to higher material costs; its disposal costs are

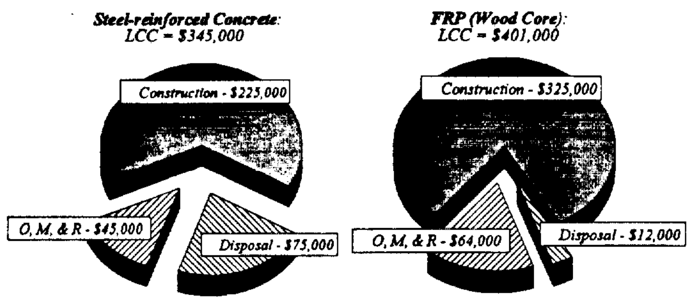

FIG. 2. Life-Cycle Cost by Life-Cycle Category

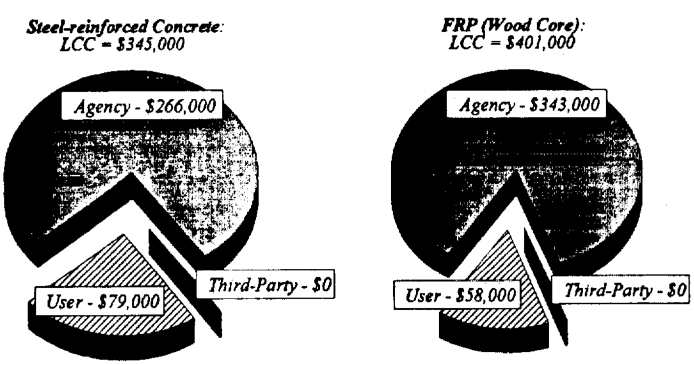

FIG. 3. Life-Cycle Cost by Cost-Bearer Category

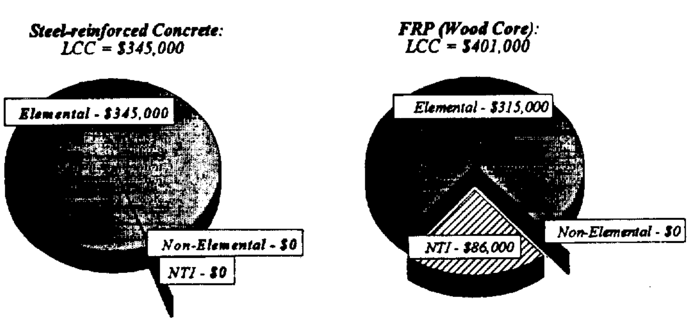

FIG. 4. Life-Cycle Cost by Project Element

lower since it can be disposed of quickly and by hand labor. The FRP's OM&R costs are higher than the concrete deck costs mainly due to the amount of new-technology-introduction costs that burden the agency and user (e.g., nondestructive evaluation of the new deck). Fig. 3 illustrates how the FRP composite deck puts less of a burden on users of the highway as measured by the user cost of driver delays, vehicle operating costs, and (expected) increased accidents. This burden is due directly to the longer time required for work on the concrete deck. While the cost to users during concrete deck work is $79,000, the cost to users during FRP composite deck work is only $58,000.

In addition to describing which components of the project generate costs, Fig. 4 helps to illustrate the short-run and long-run costs of the two deck materials. In the short run, the $86,000 in new-technology introduction costs for the FRP composite deck are true project costs, making the reinforced concrete deck the life-cycle cost-effective decking material. But if the FRP composite deck becomes accepted and its introduction costs dissipate, its long-run life-cycle cost is ($401,000 − $86,000) = $315,000, making the FRP composite deck life-cycle cost effective over the long run (this step is before sensitivity analysis, which is outside the scope of this report).

Note that the costs in Figs. 2 and 3 include these short-run new-technology introduction costs. Long-run versions of these two figures can be drawn by excluding the new-technology introduction costs from their totals.

CONCLUSION

Many new construction materials are being developed that are technically equal or superior to conventional materials. Economic methods are needed to determine whether these new materials are life-cycle cost effective relative to conventional ones. This report provides such a method.

The method does not prescribe a particular material but rather allows the project planner to choose any material that satisfies the project's generic dimensional and technical requirements. The cost classification ensures that all project-related activities are accounted for, including those activities that bring a new material into mainstream use. The life-cycle cost of competing material/design alternatives can be compared in ways useful to project budgeters (e.g., by life-cycle category), to cost estimators (by project element), to researchers and developers (by short-run and long-run costs), and to social planners (by agency, user, and third-party costs). The inherent cost uncertainty of materials and designs that are not in mainstream use can be handled with Monte Carlo simulation.

The current effort at the National Institute of Standards and Technology (NIST) is to make this new-material method accessible to engineers and project planners. Work is focused on developing user-friendly Windows-based life-cycle cost software that uses this method and includes supplemental technical information about new materials such as high-performance concrete, aluminum, and FRP composites. This software will provide planners with integrated technical and cost information.

ACKNOWLEDGMENTS

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APPENDIX I. USER COST FORMULAS

User costs accrue to the direct users of the project. For example, highway construction often causes congestion and long delays for private and commercial traffic. New bridge construction impacts traffic on the highway over which it passes. Maintenance and repair of an existing bridge, along with the rerouting of traffic, can impact drivers' personal time and the operating cost of vehicles sitting in traffic. Accidents, involving harm to both vehicles and human life, tend to increase in road work areas.

These traffic delay costs, idle-capital costs, and accident costs can be computed using simple formulas and tabulated traffic statistics from state DOTs. Three types of user cost are typically computed:

- Driver delay costs—the personal cost to drivers delayed by road work
- Vehicle operating costs—the capital costs of vehicles delayed by road work
- Accident costs—the cost of damage to vehicles and humans due to road work

Eq. 2 can be used to compute the cost to drivers of traffic delays related to road work.

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

where L = length of affected roadway or 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; and w = hourly time value of drivers. The hourly value w is typically a weighted average of commercial vehicle drivers' and personal automobile drivers' time. Vehicle operating costs can be calculated using

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

where r = weighted-average vehicle cost similar to that for (2); and the remaining parameters are the same as those in (2). Accident costs can be calculated using

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

where c_a = cost per accident; A_a and A_n are the during-construction and normal accident rates per vehicle-kilometer; and the remaining parameters are the same as those in (2) and (3).

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