



# Bridge Views



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## Fundamentals of Crack Control in Reinforced Concrete

Robert J. Frosch, PhD, PE, Purdue University

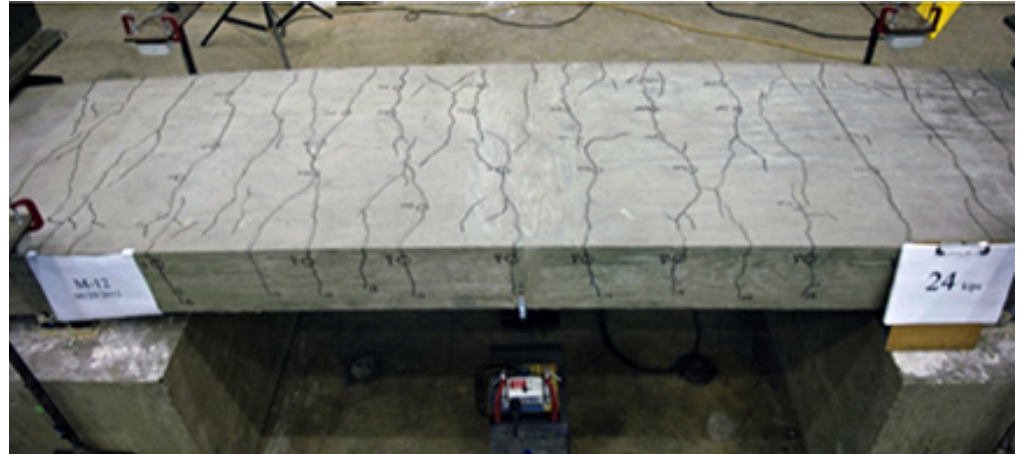


Fig. 1. Cracking Test Specimen.

Crack control is an important issue for primarily two reasons: aesthetics and durability. Wide cracks detract from a structure visually as well as may unduly alarm the public that there are structural problems. In addition, wide cracks may cause durability related problems. Cracks provide a rapid route for oxygen, water, and, depending on exposure, chlorides to reach the reinforcement, which may lead to corrosion and structural deterioration. Both analytical and experimental research continue to provide improved tools to assist in the control of cracking (Figure 1).

Current design approaches for the control of cracking focus on limiting the spacing of the reinforcement. To understand this relationship, it is important to review the fundamentals of cracking behavior which is discussed in detail in Frosch (1999). As shown in Figure 1, the crack width  $w_c$  at the level of the reinforcement can be calculated as  $w_c = \epsilon_s S_c$  where  $\epsilon_s$  is the reinforcement strain ( $f_c / E_s$ ) and  $S_c$  is the crack spacing.

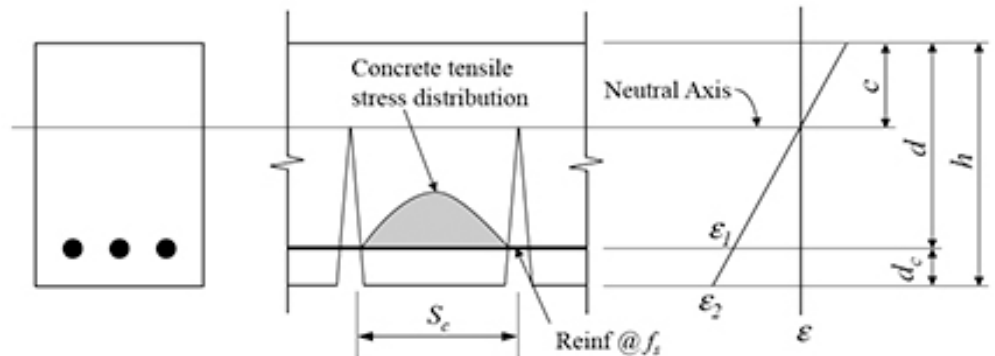


Fig. 2. Cracking Model.

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To calculate the crack width at the beam surface, it is necessary to account for the strain gradient (Figure 2). Plane sections are assumed to remain plane, and the crack width at the level of the reinforcement is multiplied by an amplification factor

$$\beta = \frac{\epsilon_2}{\epsilon_1} = \frac{h - c}{d - c}$$

resulting in the surface crack width.

Cracks develop in concrete because the tensile strength of the concrete has been exceeded. Once cracking initiates, the tension in the section is fully transferred to the reinforcement at the crack. Between cracks, tension is resisted jointly by the concrete and the reinforcement. Obviously, the tensile stress in the concrete at the crack is zero, and the tensile stresses in the concrete distribute approximately as shown in Figure 2. If there is sufficient spacing between cracks and adequate bond of the reinforcement, an increase in the reinforcement stress results in an increase in the concrete tensile stress. This increase continues until the tensile strength of the concrete is reached. The maximum concrete tensile stress occurs halfway between existing cracks resulting in formation of a crack approximately halfway between the cracks. This process continues until the crack spacing is sufficiently small that there is not enough distance to produce high enough tension between cracks; therefore, a stabilized crack pattern results.

It has been found that the crack spacing depends primarily on the

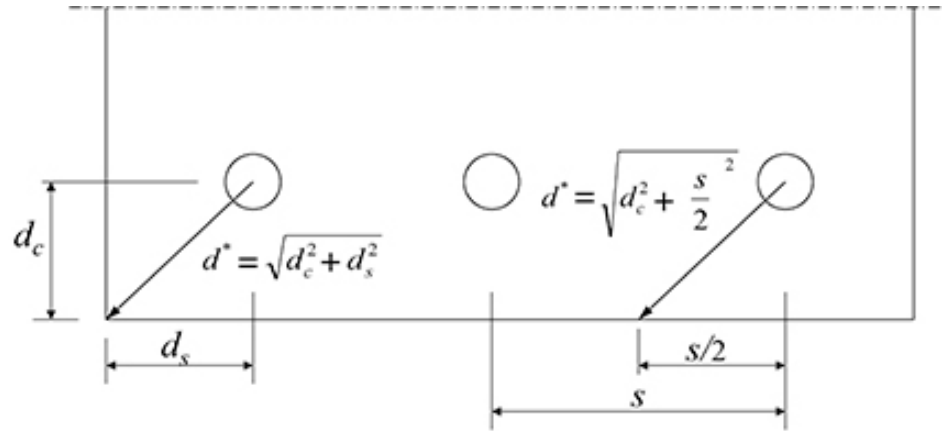


Fig. 3. Controlling cover dimensions.

maximum concrete cover. Specifically, the minimum theoretical crack spacing is equal to the distance from the center of the reinforcement to the point on the cover furthest from the reinforcement  $d^*$  (Figure 3). This spacing is the smallest that can develop as smaller spacings cannot develop sufficient tensile stresses to exceed the tensile strength of the concrete. The maximum crack spacing is equal to twice this distance as a crack may not develop halfway between the adjacent cracks. In other words, if the crack forms, the minimum spacing results.

Putting these expressions together results in the equation for the maximum crack width. This equation can be rearranged to solve for the maximum permissible bar spacing. As evident from these expressions, the spacing of the reinforcement is controlled primarily by the reinforcement stress and concrete cover.

$$w_c = 2 \frac{f_s}{E_s} \beta \sqrt{d_c^2 + \left(\frac{s}{2}\right)^2} \rightarrow s = 2 \sqrt{\left(\frac{w_c E_s}{2 f_s \beta}\right)^2 - d_c^2}$$

Maximum crack widths are typically controlled to a target value of approximately 0.016 in. This value is based primarily on aesthetics as research has shown that corrosion is not clearly, if at

all, correlated with surface crack widths (Darwin et al. 1985, Oesterle 1997). It is for this reason that the ACI 318 building code, which is based on a crack width of 0.016 in., does not differentiate between interior and exterior exposure. The equations presented in the AASHTO design specifications were derived from the expression above using a crack width of 0.017 in. While it was not felt necessary to have a more restrictive exposure condition, AASHTO decided to provide this as an option for states resulting in the Class 2 exposure condition.

The control of crack widths presented here focuses on flexural behavior and cracking on the tension face of the member. It is possible that crack widths in deep members can be greater on the side face rather than on the tension face. For this reason skin reinforcement is required which is discussed in more detail in Frosch (2002). Furthermore, crack control based on this flexural model is applicable only for the design of flexural members such as beams and slabs. For bridge decks, cracking is primarily caused by a different mechanism. Bridge decks typically develop full depth, transverse cracks which are caused

by restrained shrinkage (Figure 4). Therefore, controlling bar spacings as outlined here is not appropriate or sufficient for the control of bridge deck cracking. This topic is discussed in an earlier HPC Bridge Views bridge deck article (Frosch 2007), and more recent research provides additional guidance on the control of bridge deck cracking (Frosch et al. 2010).

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## Michigan's Experience with Ductile ECC for Bridge Decks

*Victor C. Li, University of Michigan*

### Introduction

Increasingly, DOTs are expected to maintain bridge inventories in good conditions under a tight budget. Simultaneously, there is a sense of urgency to enhance mobility and sustainability of transportation infrastructure. Given that concrete is the most used material in bridge infrastructure, it would be natural to look to new performance in concrete that could assist in meeting these challenges.

A common cause for repeated maintenance of bridge structures, especially in the northern states with severe winters and coastal states with salt-water environment, is the cracking of concrete cover that often leads to corrosion of steel reinforcement. Although it is common to use crack sealants on concrete and/

or epoxy coating of steel reinforcement to slow this process, frequent maintenance of bridge decks remains to be the norm.

A concrete that has an ability to reliably control cracking and limit the diffusion of chloride through the concrete cover in the field would be greatly beneficial to extending the service life of bridge decks, reducing downtime and enhancing driver comfort.

The intent of the Envision rating system is to standardize evaluation of the sustainability of infrastructure projects. It is applicable to projects in sectors such as energy, water, waste, transportation, landscaping, and information. In the transportation sector, project types that can use Envision include airports, roads, highways, railways, public



Fig. 1. Surface finishing of the ECC link-slab on the Grove Street Bridge in Michigan, 2005.

transit facilities, and bridges.

### What is ECC?

Engineered Cementitious Composite (ECC) is a special type of high performance concrete with tensile deformability several hundred times that of normal concrete. Cracks in ECC are limited to below 100 micron, often less than 50 micron, even under traffic induced fatigue loading. As a result, the water permeability of ECC in the field can consistent-

ly retain that of intact concrete throughout its service life. And it does so without relying on steel reinforcement. Under accelerated chloride tests, the corrosion rate of reinforcing steel inside ECC is significantly below that of reinforcing steel inside normal concrete subjected to the same mechanical loading. Further, it has been demonstrated that ECC is spall resistant. These attributes of ECC – low permeability, low chloride diffusivity, and high corrosion resistant for steel reinforcement and spall resistance in the field – make it a good candidate material for overcoming the challenges faced by those having the responsibility to maintaining bridge deck conditions.

A typical composition of ECC is given in Table 1. Depending on the exact composition, the compressive strength of ECC is in the range of 50-75 MPa, whereas the tensile ductility is 2-4%, about 200-400 times that of normal concrete. The ability of ECC to experience large deformation without fracturing is illustrated in a bending experiment shown in Fig. 2. Because ECC does not include coarse aggregates, shrinkage control should be considered especially for large surface area applications.

### Michigan’s Experience with Ductile ECC

In 2005, the world’s first ECC link-slab was installed on Grove Street Bridge in Southeast Michigan. The link-slab measuring 225

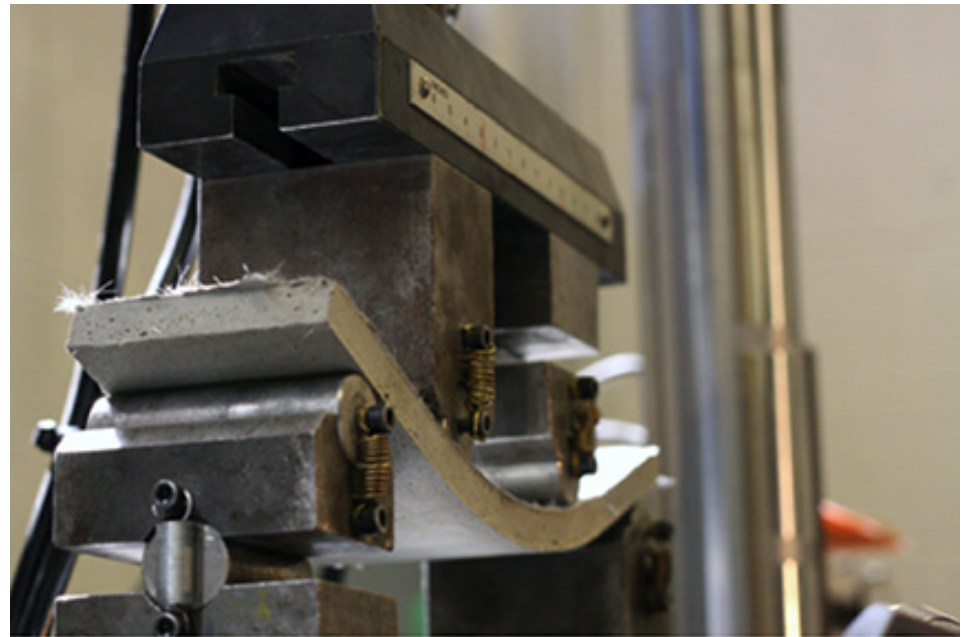


Fig. 2. ECC demonstrates an ability to deform without brittle fracturing.

mm x 5.5 m x 20 m, replaces a conventional expansion joint on a high-skew bridge. The link-slab is connected to the adjacent concrete deck through steel reinforcements, and is partially tied to the supporting steel girders through shear connectors. It is otherwise designed to stretch freely. Movement of the bridge deck induced by thermal expansion and contraction is accommodated by the ductile deformation of the link-slab, thus serving the function of an expansion joint. The ECC link-slab eliminates the typical problems of expansion joints, including joint malfunctioning, water leakage, and rusting or beam-end corrosion of the supporting girders. By this writing, almost ten years have passed since its installation. This ECC link-slab continues to serve its intended functions without any maintenance.

Despite the attentions given to the ECC link-slab, the first use of ECC was actually a small patch repair on Curtis Road Bridge over M-14 in Michigan, in September 2002. The ECC patch was placed side-by-side with a regular patch repair concrete. The deck experienced heavy 11-axle truck loading. This application of ECC demonstrated the durability of ECC under severe Michigan winter weather conditions combined with large mechanical loading. Cracks were monitored on both the ECC and the adjacent repair concrete patches. The maximum crack width in the normal repair concrete grew to about 3.8 mm over the following two years, and had to be re-repaired in late 2005. The maximum crack width in the ECC patch remained tight at approximately 50 micron for the whole monitoring period ending in 2007 when full deck replacement took place.

Another bridge deck patch repair was performed on Ellsworth Road over M-23 in Ann Arbor, Michigan, in late November of

Cement	Fine Aggregates	Fly ash	Water	HRWR*	Fiber**
578	462	694	319	7:51	26

\* High range water reducer, \*\*PVA fiber with surface coating

Table 1. A typical mix composition of an ECC (kg/m<sup>3</sup>)

2006. For this repair, a special version of ECC with high early strength of 24 MPa within 4 hours was adopted. This patch remains in good condition to this day.

### ECC's Value Proposition

ECC can extend service life of concrete bridge decks. Although the material is more expensive than normal concrete, it is competitive with repair mortars commonly adopted in small-scale repair projects. Because of the enhancement in bridge deck durability, the life-cost consideration of projects specifying ECC can make the adoption of this newer concrete particularly attractive. Furthermore, by minimizing repair needs, ECC contributes directly to enhancing

public mobility by reducing traffic interruptions, while reducing downtime and enhancing environmental sustainability. In the case of the Grove Street Bridge, life-cycle analyses conducted by the Center for Sustainability at the University of Michigan found that the adoption of ECC leads to a reduction of about 40% of carbon and energy footprints over the life-time of the bridge deck. ECC offers values to DOTs, the motorist public, and the natural environment.

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## Shrinkage Reducing Admixture Usage in Hawaii Bridge Decks

*Gerobin Carnate, Hawaii DOT*

Hawaii's climate is considered ideal for concrete construction due to its mild temperatures and moderate humidity levels year round. Rarely does the temperature rise above 90°F or drop below 65°F at lower elevations. Humidity may vary slightly on a daily basis, with an average of 63% humidity in Honolulu. Even with such a moderate climate, cracking due to creep and shrinkage is still a big concern in the design and construction of bridges. While concrete mixtures that optimize aggregate content can also minimize paste content thereby controlling shrinkage, local materials used in Hawaii have higher values of shrinkage and creep in comparison to concrete construction in other parts of the country.

The high creep and shrinkage



Fig. 1. Kualaka'i Parkway Grade Separation – No deck joints and No Shrinkage Cracks with use of SRA.

values have resulted in cracks in concrete structures when the stresses exceed the tensile capacity of the concrete. Bridge designers address cracking by installing joints within the structure, especially within the bridge deck.

The Hawaii Department of Transportation (HDOT) has continually looked for ways to reduce or eliminate the number of joints in bridge decks to cut construction and joint maintenance costs. Ultimately, the best approach in

bridge deck construction is to eliminate joints.

The Kualaka'i Parkway Grade Separation structure is a newly constructed bridge on Interstate Route H-1 in Kapolei, Oahu. The structure is a prestressed concrete spliced-girder bridge that was constructed with a high performance concrete deck mixture containing Shrinkage Reducing Admixtures (SRA) and with no deck joints. No cracks have been found in the deck during recent bridge inspections.

HDOT's usage of SRA began in early 2001 in the construction of the Keaiwa Stream Bridge on Hawaii Island. The design of the multi-span bridge included a 30-day delayed closure strip over a pier to prevent the superstructure from "lock up" due to a large skew which was analyzed to cause high stresses in the bridge deck from transverse bending. To minimize construction time the contractor requested HDOT to consider using 96 oz per cubic yard of SRA in the concrete bridge deck to reduce the shrinkage in lieu of the 30-day delayed poured closure strip. The contractor's consultant, KSF Inc., had been consulting with Japanese engineers at Taiheiyo Cement Corporation who had used SRA quite extensively as early as 1980.

To determine its effectiveness and the effects of reinforcing, a research project was undertaken by HDOT to monitor the shrinkage strains in the Keaiwa Stream bridge deck and in eight 36 x36 x 8 inch concrete specimens. These specimens were categorized into two groups, with and without the SRA and varying amounts of

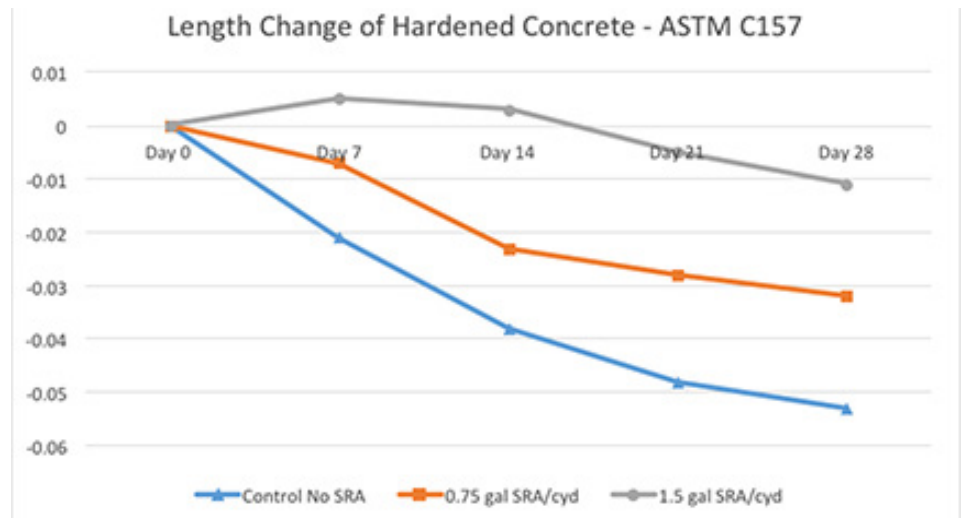


Fig. 2. Kualaka'i Parkway Grade Separation – No deck joints and No Shrinkage Cracks with use of SRA .

steel reinforcements of 0.3 to 1.2 percent. Vibrating strain gages were used to monitor shrinkage, strain and creep for one year. Results showed a 60% reduction in shrinkage in the unreinforced test specimens with SRA. Creep was also reduced by 30 percent. The reinforced sections also showed reductions in shrinkage and creep.

In addition, the Keaiwa Stream Bridge and another single –span concrete structure in Kahuku, Oahu containing SRA in the deck mixture were instrumented with vibrating wire strain gages and data collected for a year. This data also indicated a reduction of creep and shrinkage values.

The compressive strength of concrete containing SRA was reduced as compared to the baseline concrete mixture without SRA by approximately 10 to 15 percent.

Since completion of these projects, SRA has been required in all bridge deck concrete mixtures. With the incorporation of SRA, fibers, superplasticizers and synthetic air entrainment in the deck concrete, Kualaka'i Parkway was the first of several single-span

bridges constructed with no expansion or contraction joints between the integral abutments. These bridges have spans ranging from 60 feet to 180 feet in length. Examinations of the decks have shown no visible cracks resulting from drying shrinkage of the concrete.

HDOT's current concrete deck mixture has been able to achieve substantial shrinkage reduction and toughness without strength loss. Varying addition rates of SRA will result in varying costs and benefits. Local testing should be done to determine optimal addition rates for a given mix design and the desired performance of the concrete.

Concrete mix design using SRA is only one of the elements in HDOT's effort to reduce and/or eliminate joints. The overall design and construction of the bridge also play a major role in achieving the most crack free structure possible with the least amount of maintenance. However, SRA has proven to be a useful tool in a synergistic approach to prevent and limit cracking in bridge decks as well as eliminate or reduce joints in H bridge decks.

## Sustainable Bridges and Infrastructure (Part II)

Julie Buffenbarger, FACI, LEED AP, Lafarge

(Part II of a two-part series)

### Design Selection with Life Cycle Analysis

For several decades, researchers interested in the relationship between building materials, construction processes, and their environmental impacts have studied embodied energy in building materials. Embodied energy is divided into two main areas, namely the initial embodied energy and the operational energy. Simply put, initial embodied energy is the total energy consumed during resource extraction, transportation, manufacturing, and fabrication of a material/product; and is typically calculated within the boundaries of Cradle-to-Gate (factory gate) or Cradle-to-Site (site of use) to separate it from operational impacts. Operational energy is non-renewable energy consumed to maintain, repair, restore, refurbish or replace materials, components or systems during the structure's life span. Operational energy is heavily influenced by the durability and maintenance of construction materials, systems and components installed in the structure, and the life span of the structure.

Life Cycle Assessment (LCA) is a method to evaluate all the aspects connected with bridge construction and the associated environmental impacts during its entire life span, including such phases like materials acquisition, creation, transportation, use, and finally disposal of the product(s). Three reporting strategies to support impact reduction pre-

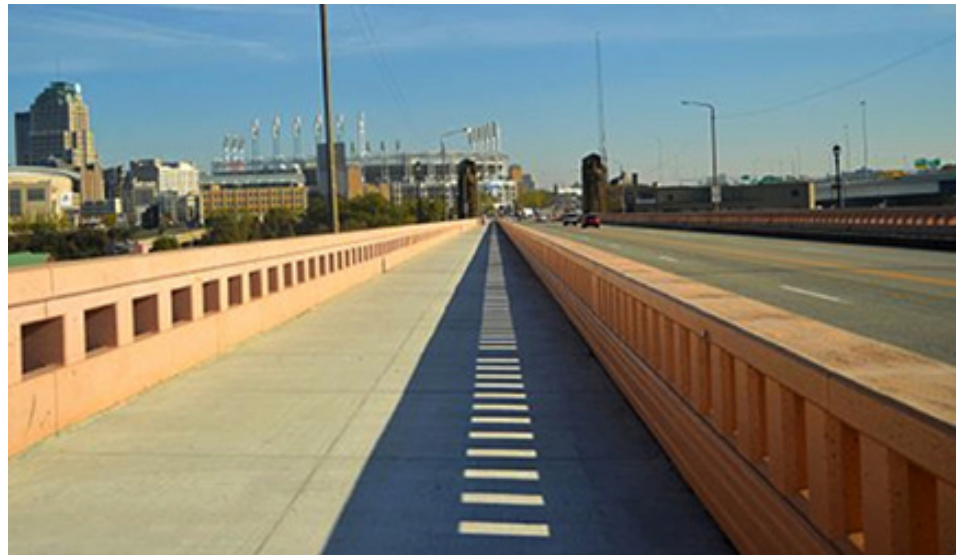


Fig. 1. Nearly 80 years after it was first constructed, the Hope Memorial (Lorain-Carnegie) Bridge is "complete." The \$4.5 million investment is consistent with the Cleveland's Complete and Green Streets law, which requires sustainable transportation options be incorporated into new road projects.

dominate: Reduced net embodied energy; Environmental Product Declarations (EPDs); or specific parameters from EPDs. An EPD, is a comprehensive, internationally harmonized, verified document that reports environmental data of products, materials or processes based on life cycle assessment (LCA) and other relevant information in accordance

with the international standard ISO 14025 (Type III Environmental Declarations). Specific parameters of EPDs may include global warming potential (GWP), ozone depletion, acidification, eutrophication, photochemical smog, ecotoxicity, resource depletion, and reduced net embodied energy.

Collings<sup>1</sup> studied embodied energy and CO<sub>2</sub> emissions data

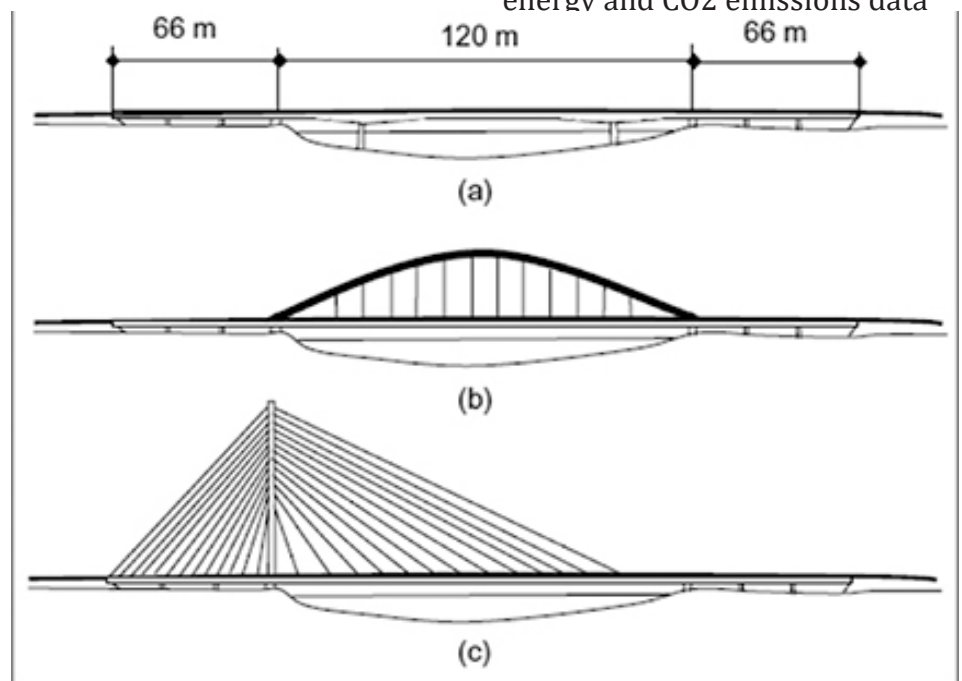


Fig. 2. Three Bridge Forms Considered in the Study: a) girder; b) arch; and c) cable stay.projects.

from different forms of bridge construction in the United Kingdom (Figure 2). Data was gathered on a moderate river bridge with a width of approximately 394 feet (120 m) and 217 feet (66 m) approaches on each side and a total deck area was approximately 46,285 ft<sup>2</sup> (4300 m<sup>2</sup>). The main river span and shorter approach span structure were evaluated.

Three commonly used construction materials were considered: steel; concrete; and a steel-concrete composite.

The concrete type used an in situ deck on a reusable shuttering system. The composite type was of steel girders supporting a concrete deck slab with permanent formwork. For the composite bridge the towers of the cable stay form were concrete and the arch steel. The steel bridge used an orthotropic deck on girders.

The embodied energy and carbon dioxide emissions generated during construction are shown in Table 1. The data illustrates that across the range of bridge forms, concrete construction consumes the least energy and produces the least CO<sub>2</sub> emissions. It additionally implies that a well-engi-

neered, longer span bridge using regional materials, recycled steel and eco-friendly concrete is similar to shorter less sustainable spans.<sup>2</sup> Subsequent LCA studies by others conducted on bridges have also shown concrete to be a favorable environmental building material in comparison to wood and steel alternatives.<sup>3, 4, 5</sup>

LCAs of structures are greatly impacted by service life. Bridges should be designed to maximize the life of the existing infrastructure. Proper structural design and detailing, material composition, high quality construction practice, and preplanned operation and maintenance routines, including durability monitoring of the structure will significantly extend service lives and offer much lower predictable operational energy.<sup>6, 7</sup>

It is the responsibility of the bridge engineer to consider both the mechanical and environmental loads effects, including future climatic conditions, and potential deterioration mechanisms and durability risks to ensure safety and serviceability over the bridge structure's entire service life.<sup>8, 9</sup> Qualitative service life prediction models should be used to link

material property improvements and infrastructure life cycle analysis. By coupling materials and structural deterioration models, a quantitative service life maintenance model and full life-cycle impact assessment can be created.<sup>10</sup> Evaluation of environmental factors, loads, materials, service life prediction models during the analysis and design stages coupled with life cycle assessment and life cycle cost optimization should become an integral part of a sustainable infrastructure design. Figure 2 shows a flow chart of durability design.

### Life Cycle Balance: Life Cycle Costing Analysis and Service Life Performance Requirements

The design of long life structures and effective life cycle management of existing structures will enable the construction of bridge infrastructure that contribute to the protection of the environment, as well as ensuring public safety, health, security, serviceability and life cycle cost-effectiveness.<sup>12, 13</sup> Development of performance-based approaches and employment of appropriate maintenance strategies is critical to ensure adequate safety, serviceability and extended service life that minimizes the risk of failure for concrete infrastructure.

The increased emphasis on life cycle cost analysis (LCCA) for projects requires that attention be focused on the service life and durability of concrete structures including costs of initial construction, continued maintenance, and eventual demolition or deconstruction. The initial selection of bridge construction

Energy	Structural Form	Embodied Energy during Construction (GJ/m <sup>2</sup> )			CO <sub>2</sub> Emissions during Construction (kg/m <sup>2</sup> )		
	Type	Steel	Concrete	Composite	Steel	Concrete	Composite
Minimum	viaduct	17.8	15.7/16.6	16.6	1484	1445/1449	1453
	girder	30.9	23.6	29.1	2513	2132	2440
	arch	49.8	34.3	48.8	3952	3536	4036
	Cable-stay	40.3	21.1/22.1	37.7	3406	3242	3372
Average	viaduct	23.5	21.1/22.1	22.1	1719	1710/1883	1702
	girder	39.3	30.6	37.0	2810	2457	2750
	arch	61.9	49.1	60.8	4326	4005	4459
	Cable-stay	50.6	43.9	47.7	3822	3726	3830
Maximum	viaduct	30.8	28.1/28.6	29.2	1891	1912/2066	1893
	girder	49.3	39.1	46.6	3045	2718	2998
	arch	75.6	60.9	74.4	4637	4410	4820
	Cable-stay	62.6	54.8	69.3	4174	4146	4244

Table 1. Embodied Energy and CO<sub>2</sub> emissions data for different forms of bridge construction<sup>21</sup>



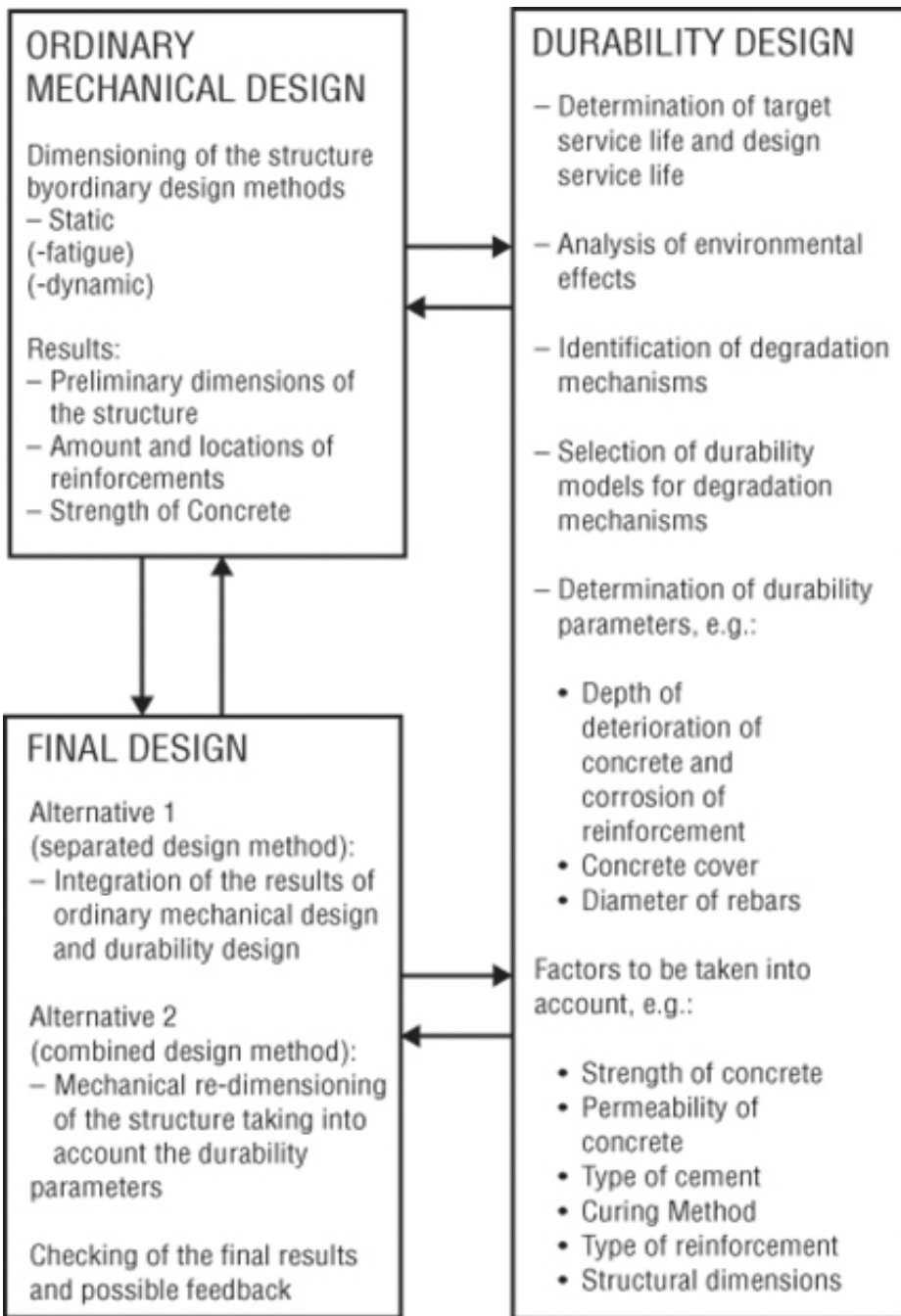


Fig. 3. Flow Chart of the Durability Design Procedure<sup>11</sup>

materials may depend on a number of complex and often intangible factors, but the total initial and long-term costs of using any construction material system is one of the most important parameters for planners and budgeters. LCCA is a necessary component in bridge management systems (BMSs) for assessing investment decisions and identifying the most cost-effective improvement alternatives. The

LCCA helps to identify the lowest cost alternative that accomplishes project objectives by providing critical information for the overall decision-making process.

When used in combination with service life performance requirements, LCCA modeling provides a balanced importance of economics, environmental and societal impacts for material or system selections for infrastructure (Figure 3).

## Sustainable Bridge Engineering Tools

CEEQUAL, Envision™, INVEST and the National Cooperative Highway Research Program's "Guidebook for Sustainability Performance Measurement for Transportation Agencies" are some recently developed rating systems and guidance tools providing similar goals; objectives; evaluation, measurement and assessment tools; as well as, design and project implementation strategies to improve the sustainable design and performance of infrastructure.<sup>15, 16, 17, 18, 19</sup>

## Future Considerations

The use of innovative design and practices such as: complementary cementing materials, ultra-high performance concretes,<sup>20</sup> high-performance fiber reinforced cementitious composites, recycled concrete aggregates, internal curing, photovoltaic and LED lighting, vertical wind turbines, and accelerated bridge construction can all impact LCA and LCCA. In addition, high-speed and high-resolution, nondestructive evaluation (NDE) technologies for inspection, evaluation, and performance monitoring feedback to deterioration mechanisms that allow for timely preventive, corrective, and improvement measures to preserve good structural and functional performance with extended service life. Considerations should also include maintenance management programs with inclusion of non-invasive devices and sensors (e.g., smart sensors, embedded sensors and systems) that permit both periodic and continuous performance evaluation and accurate condition assessment.<sup>21</sup>

Finally, designing for adaptability and deconstruction provide strategies for climate change adaptation and end of life decommissioning.<sup>22</sup>

In closing

Bridge and highway infrastructure systems, represent an enormous investment of materials, energy, and capital, resulting in significant environmental burdens and social costs. Development of innovative materials, construction practices, and employment of appropriate inspection and maintenance strategies is critical to ensure adequate safety, serviceability and extended service life that minimizes the risk of failure for structures and infrastructure. Design, construction, maintenance, climate adaptation and resiliency are all considerations to secure long-term sustainability of new bridge assets. Hence, enhancing the resilience of bridge infrastructure through designed robustness, durability, longevity, disaster resistance, and safety should also be a priority for the bridge engineer.

*Ms. Buffenbarger is the current Chairman of ACI's Sustainable Concrete Committee. For more information, she can be contacted at [julie.buffenbarger@lafarge.com](mailto:julie.buffenbarger@lafarge.com).*

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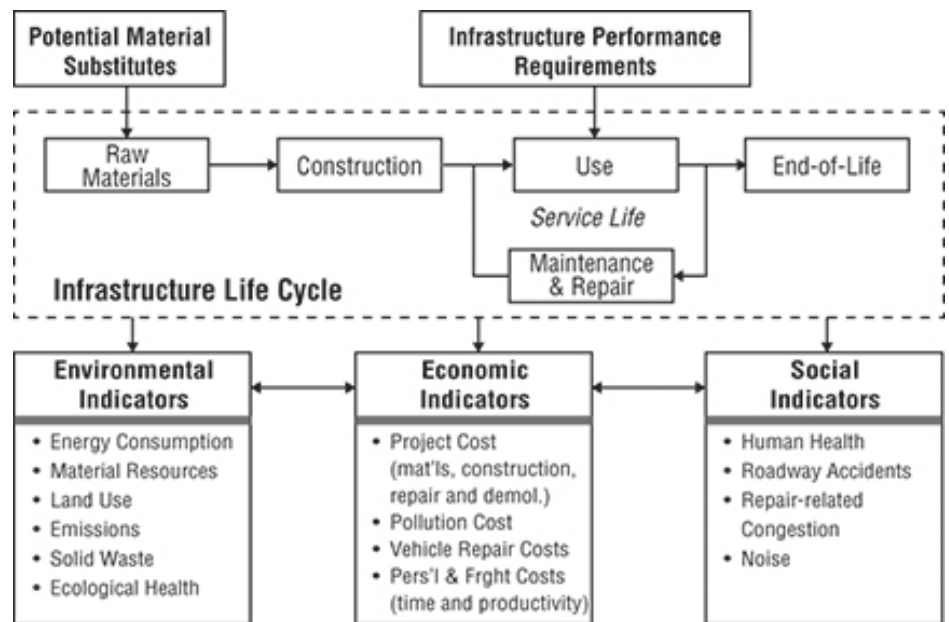


Fig. 4. Macroscale Life Cycle Modeling of Infrastructure Systems<sup>14</sup>

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