Thoughts about Durability and Service-Life Design of Bridges

by Dr. Elizabeth I. Wagner and Dr. Michael C. Brown, Wiss, Janney, Elstner Associates Inc.

Structural design of bridges has evolved over the last century, transitioning from allowable stress design to load factor design to load- and resistance-factor design (LRFD).[1] Currently, the design of new bridges includes a heightened focus on designing for durability. More and more, owners are requiring that bridges be designed with durability in mind, with specifications commonly calling for bridges to achieve service lives of 75 or 100 years—and sometimes beyond.

Service Life versus Design Life

What does it mean to achieve a 75- or 100-year service life and how is that different from the 75-year design life in the Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*?[1]

Just as the objective of structural design is for a structure to continue to support anticipated loads over its *design life*, the goal of durability design is for the structure to remain serviceable under anticipated environmental exposures for its *service life*. A structural design may consider changes in loads over time resulting from construction, service loads, or extreme events, and may also consider changes in the capacity or strength of the component due to concrete curing, creep, or fatigue. Similarly, a durability design must consider changes in environmental exposures and in material properties and conditions due to deterioration over time. Designing according to the AASHTO LRFD specifications or a similar structural design code is intended to result in a bridge that will continue to meet minimum strength and serviceability requirements over its design life (typically 75 years). However, these codes have traditionally been developed as a minimum structural safety requirement and do not guarantee that the materials or ancillary components (such as joints and bearings) will be able to provide that strength and serviceability for that same design life. The industry has come to recognize that design for durability is needed, such that the combination of materials, design details, construction practices, and planned maintenance activities will enable the bridge to achieve its target service life.

In the context of durability design, end-of-service life is defined as the time at which deterioration exceeds a particular limit, which must be specified. Simply stating "design for a 100-year service life" does not clearly define the requirements. For example, when the service life of a component (such as a bridge deck or pier cap) is limited by corrosion of the reinforcing steel, the target service life might be defined by the time at which corrosion would be expected to first initiate in the reinforcing steel, the time at which corrosion would first cause damage (such as cracks, delaminations, or spalls) to the concrete, or the time at which corrosion-related damage would affect a certain percentage of the component's surface and require structural repair. When service life is limited by other types of deterioration, such as cyclic

Twin core holes from a reinforced concrete bridge deck. The crack on the right is aligned with reinforcement. Materials, design details, construction practices, and planned maintenance activities will enable a bridge to achieve its target service life. All Photos: Virginia Department of Transportation.

A built-up asphalt and sheet membrane being placed on a highway bridge deck as part of a deck rehabilitation. Planned maintenance activities are an important aspect of a bridge durability plan.

freezing and thawing or alkali-silica reaction (ASR), the specific limit may be more difficult to define in quantitative terms. In such cases, the target service life may instead be defined as the time at which deterioration of the concrete due to any of these mechanisms occurs, or occurs to such an extent as to affect the structural capacity of the component.

Durability is affected by both the macroenvironment where the structure is located and by the microenvironment of individual components within the bridge. Just as with the AASHTO LRFD specifications, different limit states may, and often do, apply to different components within a single structure. For example, a buried component such as a pile will have different exposure and may have a lower threshold for allowable damage at the end of service than a bridge deck; if the thresholds vary, it is because the structural importance of components differs, and identification and remediation of deterioration is much easier for a bridge deck than it is for a buried pile. Likewise, different structural components may also have different target service lives, with replaceable components such as bearings and joints often having shorter target service lives than nonreplaceable components such as substructures and abutments. In some cases, it may not be possible for a component to achieve the overall target service life, and replacement of that component (for example, a joint, bearing, coating, or wearing surface) will need to be considered in the structural design as well.

Designing for Durability

How does one design for durability and a target service life? Once the end-of-service criteria have been defined for a bridge and its individual components, the durability engineer will examine the components and their environmental exposures, identify the relevant deterioration mechanisms, and develop a protective strategy to provide confidence that each component and the overall structure will achieve their target service lives.

There are several approaches for developing a protective strategy

Definitions

Design life—The period of time on which the statistical derivation of transient loads is based; this period is 75 years for the AASHTO LRFD specifications.[1]

Target service life—The assumed period of time the bridge is expected to remain in operation, without rehabilitation or significant repair, and with only routine maintenance (intended life). This maintenance would include replacement of renewable elements.[2]

A combination of carbon, epoxy-coated, and galvanized steel reinforcement at the intersection of bridge superstructure components prior to concrete placement.

for durability, and typically a combination of approaches will be used. For deterioration mechanisms whose physical principles are well understood, such as corrosion, service-life modeling can be used to predict the most *probable* service life for the component. The modeling will consider options for materials (such as reinforcement types and concrete mixture proportions), component details (such as reinforcement cover and geometric configuration), construction practices (such as tolerances and placement and curing methods), and planned maintenance activities (such as reapplication of coatings and sealants, repairs, and overlays). In this way, multiple protection strategies can be efficiently examined, and the strategies most likely to achieve the target service life can be presented to the structural designer and owner for consideration.

For other deterioration mechanisms that cannot currently be modeled, such as deterioration due to freezing and thawing or ASR, development of a protective strategy will often rely on *avoidance* as an approach.[2,3] This typically entails laboratory testing to confirm that the materials used will resist or are not susceptible to a particular form of deterioration. In some cases, design teams rely on industry best practices and extensive empirical experience with specific design approaches to determine how to provide protection against certain deterioration mechanisms that are not practical or possible to evaluate in the laboratory. This approach is commonly referred to as *deemed to satisfy* in service life design guides.[2,3]

Durable Materials

How can we use durable materials and better construction practices now to avoid maintenance issues later? While the details of a particular protective strategy will be unique to the specific component and environmental conditions present, all protective strategies rely, to some extent, on the durability of the materials selected.

Concrete may need to have low permeability to resist chloride and sulfate ingress, and low shrinkage potential to resist cracking. Service-life modeling can be used to determine the minimum performance requirements for concrete to achieve a specific service life with respect to corrosion, and laboratory testing can be performed on candidate concretes to confirm that these and other performance requirements can be achieved. A combination of low water–cementitious materials ratio and supplementary cementitious materials (SCMs) such as fly ash, slag, or silica fume may be needed to provide sufficiently low-permeability concrete to achieve a 75- or 100-year service life, and these mixture proportions can have additional benefits with respect to mitigating other types of material degradation, such as sulfate attack or ASR.

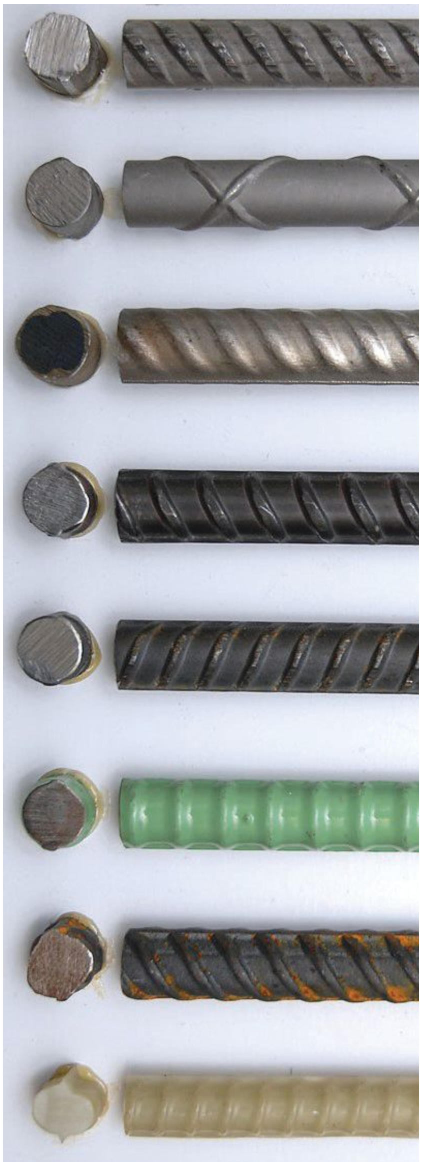
For certain environments and structures, corrosion-resistant reinforcement may also be necessary to achieve a 75- or 100-year service life. Coated steel reinforcement such as epoxy-coated or galvanized bars can delay the time to corrosion initiation compared with uncoated black steel. Uncoated low-carbon chromium and stainless steels can resist more aggressive concentrations of chloride ions compared with uncoated black bar—but we must be mindful that there are many different grades of such steels with different mechanical and corrosion-resistant properties. Nonmetallic reinforcement, such as glass-fiber-reinforced-polymer composite or carbon-fiber-reinforced-polymer bars, can also be used as an alternative to steel reinforcement, but its use may require special consideration for structural design and fabrication.

One challenge that may be encountered when designing structures for durability is the potential trade-off between short-term strength and long-term durability. The proportions of cementitious materials in a concrete mixture can be increased to achieve high early strengths, but these changes may increase shrinkage and cracking potential. Also, the high dosages of SCMs that are sometimes needed to achieve the target durability characteristics may result in slower strength development and therefore extended construction schedules. Durability engineers can work with designers and contractors to balance the need for timely strength gain with the competing need for long-term durability.

What about the Details?

Using durable materials is key to achieving long service lives; however, without proper design details, a structure may still not achieve its target service life. If the cover over reinforcement is too shallow, it may not provide enough concrete to protect the reinforcement from corrosion, whereas too much cover may increase crack widths and provide a more rapid pathway for chloride and

Different types of reinforcement. Shown from top to bottom are:
Stainless steel 316LN
Stainless steel 304
Stainless steel clad carbon steel
Low-carbon chromium steel
Low-alloyed duplex stainless steel 2101
Epoxy-coated carbon steel
Carbon steel
Glass-fiber-reinforced polymer



other contaminants to enter the concrete and reduce its durability.

Just because a bridge is designed for a 100-year service life does not mean it is designed for no maintenance. A bridge may have all the right concrete materials, reinforcement type, and design cover to resist deterioration over the design service life, but if the deck drainage system fails and causes runoff to flow onto the pier cap and substructure, or if the joints lock and cause the adjacent concrete to spall, then unanticipated deterioration may reduce the service life of the structure. Good quality control during construction and routine inspection and maintenance are important to achieving service life and should be part of any durability plan. Designing for durability should also facilitate access for inspection and consider replaceable components.

What More Is There to Know?

Durability has become an increasingly important consideration in the design of new bridges, with guidance recently published by AASHTO facilitating its incorporation throughout the industry.[2] (See the FHWA article on service-life design on page 62.) Nonetheless, the industry would benefit from a better understanding of physical principles for many of the modes of deterioration affecting bridge components, and the development of suitable models for these types of deterioration. In addition, the rapid evolution of construction materials coupled with changing climate and exposure conditions have the potential to affect service life in unexpected ways. Yet, with an added focus on durability, we can now aspire to develop structures that can withstand these uncertainties and achieve service lives of 75 or 100 years—or more.

References

1. American Association of State Highway and Transportation Officials (AASHTO). 2020. *AASHTO LRFD Bridge Design Specifications*. 9th ed. Washington, DC: AASHTO.

2. AASHTO. 2020. *Guide Specification for Service Life Design of Highway Bridges*. Washington, DC: AASHTO.

3. *fib* (International Federation for Structural Concrete). 2006. *Model Code for Service Life Design. fib* Bulletin 34. Lausanne, Switzerland: *fib*.

Dr. Elizabeth I. Wagner is a senior associate at Wiss, Janney, Elstner Associates Inc. in Northbrook, Ill., and Dr. Michael C. Brown is an associate principal at Wiss, Janney, Elstner Associates Inc. in Falls Church, Va.

EDITOR'S NOTE

As discussed in this article, designing a structure and its components for a specific service life involves more than increasing concrete cover. Suitable knowledge of exposure conditions, deterioration processes, construction materials, and construction and maintenance practices is required to make sound choices during design. Case studies of designing for service life, including full probabilistic design, partial factor design, deemed to satisfy design and avoidance of deterioration can be found in in "International perspective: Extending the service lives of bridges," which appeared in the January–February 2008 issue of PCI Journal. *https://doi.org/10.15554/pcij.01012008.121.142.*