

STRUCTURAL DESIGN

design issues for structural engineers

Durability of Reinforced Concrete

By Paul Noyce and Gina Crevello

Paul Noyce is a concrete and material durability expert. Paul is the Chairman of National Association of Corrosion Engineer's (NACE) Standard Technical Group 01 for Reinforced Concrete. He may be reached at pnoyce@e2chem.com.

Gina Crevello is material conservator. Gina is on the board of the Association for Preservation Technology International. She may be reached at gcrevello@e2chem.com.



Historically, reinforced concrete has been thought of as very forgiving when it comes to the amount of time the material performs in service. Although there is a lot of truth to this, the environment inevitably can shorten reinforced concrete's life expectancy, resulting in costly repairs and disruption to everyday life.

When we think of durable concrete, the Pantheon in Rome comes to mind. This structure has been in service for well over 2000 years. If Roman concrete can last for centuries, surely current construction materials should be suitable to serve a 50 or 100 year design life. In some ways, assumptions on material durability may have influenced early specifications which fail to address material performance over time.

As our understanding of durability increases, we expect increased performance of the materials we put into service. In the instance of landmarks or monuments, we want to build and preserve these structures in perpetuity. As we are constantly striving to improve material performance, we simultaneously want to be more sustainable in our approach, and be proud of what we build. Like

Roman engineering, attaining durable structures with an extended service life, like the Pantheon, should be our end goal.

A vast amount of research was carried out on the durability of concrete from the 1970s to the 1990s and a great deal of technical knowledge was achieved. It is now possible to utilize this information in our designs to provide a level of confidence to owners on the future performance of reinforced concrete structures.

To make reinforced concrete more durable, a design approach has to be considered; the

performance over time should be modeled where various dimensions and material specifications can be reviewed. This type of design is referred to as service life design (SLD), where the engineer can demonstrate performance of the selected structure over time, as seen in *Figure 1*.

The SLD has to demonstrate the performance and degradation of the engineering materials. Both of these are heavily influenced by the environment which, in turn, is affected by local macro and micro climates. In addition to understanding the environment, knowledge of local materials is required, as this too varies greatly. Because of these variations, material performance and service life should be treated stochastically.

Performance and Degradation

The performance of a structure is typically seen as how well it is functioning related to its use. This can be further expressed as the performance of key principles like load capacity, stability, safety and visual appearance. Performance is regarded by many as a quantifiable property and is always a function of time.

When considering time in evaluating performance, degradation of the structural materials is regarded as the most important factor. This links the structure's performance directly with the durability of its materials. ASTM E632, *Standard Practice for Developing Accelerated Tests to Air Prediction of the Service Life of Building Components and Materials*, defines durability as the capability of maintaining the serviceability of a product, component, assembly, or construction over a specified time. Serviceability is viewed as the capacity of the above to perform the function(s) for which they are designed and constructed.

Degradation is the reduction or decrease in performance over time and can be understood

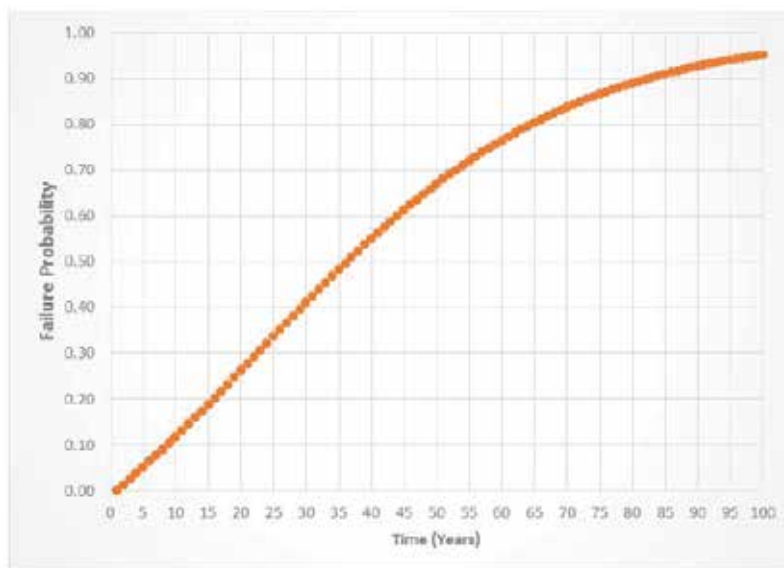


Figure 1. Probability distribution function of service life.

as the inverse of performance; therefore, measuring degradation allows one to assess performance related problems. Performance is then measured by a minimum acceptable level, while degradation is set by a maximum acceptable level. These levels are known as durability limit states and can be defined for future performance measurements. The limit state can be set to either an ultimate or serviceability limit, which defines the service life and ultimately the performance requirements of the structure.

When looking at degradation problems in reinforced concrete, the two main materials, the concrete and the reinforcing steel, are what impact the durability of the structure. The symbiotic relationship between reinforced concrete and steel ensures that, if defects exist within the original design or material selection and if load factors that enhance corrosion are present, deterioration will ensue. In turn, the environment in which these materials are installed impacts and defines their long term performance and degradation.

Service Life

Service life of materials can be assessed by their expected lifetime, or their acceptable period of use in service. As service life can be

expressed in three ways, technical, functional or economic, then different use requirements are needed. In assessing service life as a business policy, financial tools and mathematical calculations can be carried out to develop a maintainability and reliability analysis.

The questions regarding service life and maintenance are always related as maintenance routines are carried out during the service life of the structure. Maintenance activities, which influence service life, need due consideration. This changes the overall definition of service life which is stated as “when routinely maintained” as defined in TC 71-PSL *Systematic Methodology for Service Life: Prediction of Building Materials and Components* (Masters and Brandt, 1989).

It is always the requirement of the owner to define the service life requirements and set forth the duration requirements, which sets the target service life.

Probability of Failure

When a target service life is set, a stochastic durability design will involve a definition of the maximum probability of not reaching a certain limit state. These limit states can be either an ultimate limit state (ULS) or a serviceability limit state (SLS).

Two distinct types of failure exist, as either a durability failure or mechanical failure. However, in most instances, a material durability failure will be responsible for the mechanical failure.

A maximum failure probability has to be set and defined by evaluating the consequences of the risk of failure. The risk is defined as the multiplication of the probability of failure by the amount of damage (Kraker, de Tichler and Vrouwenvelder, 1982).

When considering how to set the required probability of failure, social, economic and environmental criteria should be considered. For social criteria, the importance of the structure and the consequences of failure, where human lives are at risk, is essential. Economic criteria should consider the financial consequences of disruption due to failure when these are considerably more than the construction cost. As with environmental and ecological criteria, consideration is due to either an environmental disaster or in line with ecological principles.

Probability of failure can be applied during the design phase of new structures or to existing structures, as the principles are the same. The only significant difference is that the margin of safety used for existing structures will be much lower than new construction.

continued on next page

ADVERTISEMENT—For Advertiser Information, visit www.STRUCTUREmag.org

The Power to Pass®
www.ppi2pass.com

Resolve to Get Licensed With PPI

In January only, **save 15%** on **select exam review materials** with **Promo Code NQ10D**

100% GUARANTEE PASSING 100% GUARANTEE

Live Online Review Courses

Structural Mechanics

FE CIVIL PRACTICE MANUAL

Structural Engineering Reference Manual

Civil Engineering Reference Manual for the PE Exam

New Edition by Michael R. Lindeburg, PE.

Prepare to Pass the FE, PE, or SE Exam
PPI is the leading publisher and provider of review courses, references, practice exams, study tools, online practice, and the power to pass.

The Choice of Over 3 Million Professionals Since 1975

Visit ppi2pass.com or contact us at info@ppi2pass.com or 650-593-9119 to learn more.

Durability Design

Conceptually, a durability design is based around safety, where the structure must resist failure by various hazards it is exposed too. Safety has typically been applied to structural mechanics; however, we should not be so restricted in our design when dealing with the performance of materials. The use of this technique is increasingly advocated for dealing with durability and service life problems (Siemes, Vrouwenvelder and van den Beukel, 1985).

By incorporating time into the design, we can now value the degradation of the materials as part of the overall problem. This time-based design has to set performance related requirements to ensure that the structure fulfils its long term service life goals for safety. This then has the effect of forcing the designer to ensure that the material selection will achieve the long-term durability requirement for the service life goals.

The Environment

When considering a durability design, a key understanding of the environment and the exposure of the materials is essential in achieving a good design. The building code requirements for structural concrete, the American Concrete Institute's ACI 318-14, defines exposure categories and classes as shown in *Table 1*. BS EN 206:2013: *Concrete Specification, Performance, Production and Conformity*, also provides exposure classes for concrete durability, as shown in *Table 2*.

Although both these tables differ overall, it can be seen that they both consider the degradation of the materials. ACI categories are broken down by a damage mechanism and then class, with a variation of severity. As with BS EN 206:2013, the class is broken down based on wet and dry cycles, with various corrosion risks associated with a letter in the exposure class.

As with most situations, a series of environments and contaminants can coexist on the same structure, so the design engineer must pay attention to this in the durability design. This can be extremely

Table 1. Exposure categories and classes (ACI 318R-14 Table 19.3.1.1).

Category	Class	Condition	
Freezing and Thawing (F)	F0	Concrete not exposed to freezing-and-thawing cycles	
	F1	Concrete exposed to freezing-and-thawing cycles with limited exposure to water	
	F2	Concrete exposed to freezing-and-thawing cycles with frequent exposure to water	
	F3	Concrete exposed to freezing-and-thawing cycles with frequent exposure to water and exposure to deicing chemicals	
Sulfate (S)		Water-soluble sulfate (SO_4^{2-}) in soil, percent by mass ^[1]	Dissolved sulfate (SO_4^{2-}) in water, ppm ^[2]
	S0	$\text{SO}_4^{2-} < 0.10$	$\text{SO}_4^{2-} < 150$
	S1	$0.10 \leq \text{SO}_4^{2-} < 0.20$	$150 \leq \text{SO}_4^{2-} < 1500$ or seawater
	S2	$0.20 \leq \text{SO}_4^{2-} \leq 2.00$	$1500 \leq \text{SO}_4^{2-} \leq 10,000$
	S3	$\text{SO}_4^{2-} > 2.00$	$\text{SO}_4^{2-} < 10,000$
In Contact with Water (W)	W0	Concrete dry in service Concrete in contact with water and low permeability is not required	
	W1	Concrete in contact with water and low permeability is required	
Corrosion Protection of Reinforcement (C)	C0	Concrete dry or protected from moisture	
	C1	Concrete exposed to moisture but not to an external source of chlorides	
	C2	Concrete exposed to moisture and an external source of chlorides from deicing chemicals, salt, brackish water, seawater, or spray from these sources	

¹ Percent sulfate by mass in soil shall be determined by ASTM C1580.

² Concentration of dissolved sulfates in water, in ppm, shall be determined by ASTM D512 or ASTM D4130.

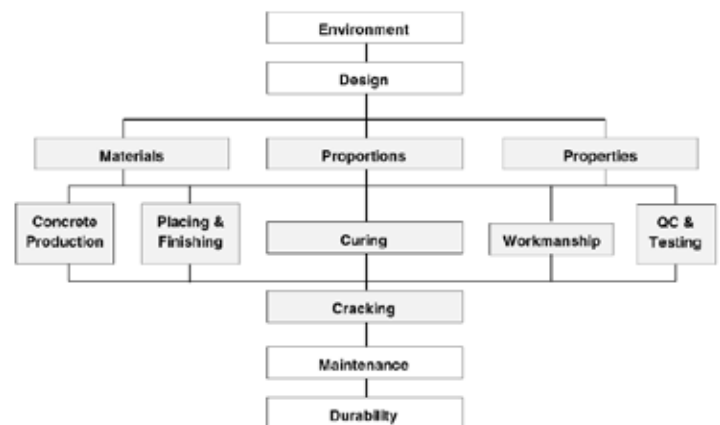


Figure 2. Holistic approach to durability. Courtesy of NRMCA.

NEW

ADVERTISEMENTS—For Advertiser Information, visit www.STRUCTUREmag.org



STEEL DECK INSTITUTE



STEEL DECK INSTITUTE

DIAPHRAGM DESIGN

4

The Fourth Edition of the SDI Diaphragm Design Manual (DDM04) complies with the requirements of the new ANSI/AISI S310-2013 North American Standard for the Design of Profiled Steel Diaphragm Panels. It includes new and expanded design examples and diaphragm strength tables.

NOW AVAILABLE

at www.sdi.org

Table 2. Exposure classes and class descriptions (BS EN 206:2013).

Exposure Class	Class Description	Corrosion Risk
X0	For concrete without reinforcement or embedded metal where there is no significant freeze/thaw, abrasion or chemical attack	No risk of corrosion or attack
XC1	Dry or permanently wet	Corrosion induced by carbonation
XC2	Wet, rarely dry	
XC3/4	Moderate humidity or cyclic wet and dry	
XD1	Moderate humidity	Corrosion induced by chlorides other than from seawater
XD2	Wet, rarely dry	
XD3	Cyclic wet and dry	
XS1	XS1 Exposed to airborne salt but not in direct contact with sea water	Corrosion induced by chlorides from seawater
XS2	Permanently submerged	
XS3	Tidal, splash and spray zones	
XF1	Moderate water saturation without de-icing agent	Freeze/thaw with or without de-icing agents
XF2	Moderate water saturation with de-icing agent	
XF3	High water saturation without de-icing agent	
XF4	High water saturation with de-icing agent or sea water Chemical attack (ACEC classes) Refer to BS 8500-1 and Special Digest 111	

complex on some structures but, if overlooked, can result in a degradation failure in an unacceptable period, which can cost many millions of dollars.

As we repair structures today, durability and the environment are not considered enough in their role in leading to premature and costly maintenance repairs. The most deleterious durability failure of concrete is related to corrosion of the embedded reinforcing steel, which subsequently causes damage to the surrounding concrete and results in millions of dollars in damage, repair and associated 'indirect' costs.

Summary

In summary, it is essential that a holistic approach is used for the design of durable concrete structures by considering multi-faceted aspects of the structure, the structure's relationship to its surroundings, appropriate material selection, the utilization of proper construction methods, adequate quality control and planned maintenance. *Figure 2* provides an overall holistic approach to the considerations required to provide durable concrete structures.

As we can see from *Figure 2*, the overall approach to durability goes beyond the design engineer's work. By reducing QA on a construction project due to cost and budget constraints, the long

term performance of a building or a structure can be drastically affected. QA is still, in our opinion, one of the major factors in achieving long term durability of concrete

structures. Whether designing new or fixing existing, attention to the installation of the work is paramount to the structure's long term survival in our ever changing environment. ■

Design Aids and Solutions.
Analysis, design, done.

Use promo code **DESIGN-15** and **save 15%** on our popular design guides at www.crsi-webstore.org.

CRSI Concrete Reinforcing Steel Institute

24/7 continuing education and FREE technical and informational downloads at www.crsi.org!

ADVERTISEMENT For Advertiser Information, visit www.STRUCTUREmag.org