PART I

DEGRADATION, SAFETY, AND RELIABILITY OF STRUCTURES
INTRODUCTION

In any condition assessment, it is important to recognize two fundamental categories of existing or potential performance failure within buildings and other structures: defects and deterioration. A defect, as used here, is the nonconformity of a component with a standard or specified characteristic. Defects may be introduced through poor design, manufacturing, fabrication, or construction before a structure begins its service life and (less frequently) by inappropriate operations and maintenance during its service life. Deterioration, as used here, is the gradual adverse loss of desired material properties. Eventual deterioration is normal for most construction materials owing to aging and weathering processes, and it must be addressed through strategic maintenance, repair, or replacement to avoid unwanted distress.

Defects may influence the rate of deterioration or may initiate premature deterioration for materials; hence the two are often involved in a cause-and-effect relationship (Fig. 1.1). This chapter provides a summary of common defects and deterioration...
FIGURE 1.1 Defect (improper exterior waterproofing) that caused deterioration (corrosion of steel box beam).

mechanisms observed in existing construction. Identifying and understanding defects and deterioration are critical in extending the service life of existing structures. Without detection through condition assessments and subsequent remedy, defects and deterioration may lead to failure of components, systems, or even entire structures.

During a condition assessment, determining whether deterioration is natural or premature may help to identify defects within the system. However, deterioration can only be identified as “premature” if the expectations for normal service life are understood. Therefore, this chapter also discusses durability, the relationship between the expected service life (design life) of building materials and their actual service life in the absence of uncontrolled defects and deterioration. Finally, a glossary is provided for terms used commonly in structural condition assessments.

DEFECTS AND DETERIORATION

A condition assessment of an existing structure may be performed for a number of reasons, including (but not limited to) determining whether a structure is safe for public occupancy; documenting the condition of existing structures prior to performing construction nearby; evaluating the existing condition as part of a “due diligence” survey prior to purchase of a building; determining whether a structure is suitable for a change in usage; establishing code compliance or determining areas of noncompliance to be remedied; and determining the cause and appropriate remedy of problems that elicit tenant complaints, such as leaks, excessive floor vibrations, or trip hazards. In these
instances, the purpose of a condition assessment is to identify the pervasiveness and severity of distress, defects, and deterioration, if any. Identifying the causes of such conditions is usually necessary to design proper remedies.

Defects

Defects are introduced most commonly during design, manufacture, fabrication, or initial construction; therefore, they are typically present at the beginning of the service life of a structure. Latent defects may be present during initial construction and lie dormant prior to manifesting themselves. Specifically, this section addresses three categories of defects: design defects, product defects, and construction defects.

Design Defects. In professional engineering design offices, it is common practice for designs to be peer reviewed, and many design errors are prevented by this process. However, defects in design often are created by poor detailing, insufficient detailing, or a lack of attention to constructability of details.

There is also occasional abdication of design responsibility that transcends errors or omissions. For example, it is common engineering practice to show on structural details the size and position of shelf angles to support brick masonry veneer but only to indicate the masonry by a phantom line, implying that the masonry itself is trivial to the engineer. A leading cause of masonry distress, including cracking, spalling, and collapse, is the lack of coordination between the structural steel and the supported masonry. A lack of expansion joints below shelf angles may lead to masonry crushing (Fig. 1.2) or a systemic failure such as bowing of the entire wall. These failures can

![Masonry crushing due to lack of expansion joint below shelf angle.](image)

**FIGURE 1.2** Masonry crushing due to lack of expansion joint below shelf angle.
be prevented by the engineer providing not only the traditional structural details but also the details pertaining to the interface between structural and architectural elements.

**Product Defects.** Poor product performance may be attributed to the manufacturer, the fabricator, and/or the designer. It is the responsibility of the designer to research and specify the appropriate product for a given application. Manufacturers’ representatives often work closely with designers to assist in the selection of products for construction applications. Reputable manufacturers have vast experience with the performance of their products in different applications and have quality assurance programs that include product testing. However, defects still may be introduced at the factory; while some sources of defects are material-dependent, others may be the result of poor quality control, such as the introduction of contaminants in manufacturing or improper material storage. Errors in fabrication also may qualify as product defects. For example, if a steel column is fabricated with an out-of-straightness that exceeds the AISC-specified fabrication tolerances, forces may be introduced in the member under loading that were not accounted for in the initial design process.

**Construction Defects.** Construction defects commonly are introduced when there is a breakdown in communication between the various groups of professionals and technicians that work separately to produce a structure. Poor communication between design professionals can lead to numerous problems, such as conflicting drawings and specifications, interference between structural elements and nonstructural systems, or misalignment of systems between stories.

Many defects are attributable to errors that occur during construction. For example, in concrete construction, defects that arise during the construction process may be due to improper placement, consolidation, curing, or finishing. Improper location of reinforcing and/or insufficient concrete cover are common sources of deterioration and subsequent distress in parking structures. Fabrication errors, such as misaligned bolt holes, are common defects in steel construction. With proper preparation and review of shop drawings, as well as field monitoring by the design team, many of these types of defects can be prevented.

**Deterioration**

Unlike defects that are typically present at the beginning of the service life of a structure, deterioration of a material or system is time-dependent. While some forms of deterioration may develop early in the service life of a structure, others are a matter of the aging of a material or system. Deterioration often is initiated or accelerated by the presence of a defect or the introduction of a catalyst. Water is the most significant catalyst for deterioration; approximately half of all failure mechanisms identified in construction involve water, including some subtle interactions. For example, overstress may not be directly dependent on water, but the strength of wood and masonry may be affected by the presence of water, thus exacerbating deterioration due to loading. In weathering and biological or chemical attack, water is the primary catalyst for deterioration. Water-induced mechanisms include (but are not limited to) decay, corrosion, freeze-thaw action, soil erosion, settling, and upheaval. The deleterious presence of water is not limited to naturally occurring events, such as rainfall, but may be attributed to infiltration of water due to construction defects.

Several types of deterioration catalysts or degradation factors may be classified. ASTM E632, “Standard Practice for Developing Accelerated Tests to Aid Prediction of the Service Life of Building Components and Materials,” categorizes degradation factors that initiate or accelerate the deterioration of building materials and components as follows:
Weathering factors. Deterioration from exposure to water, temperature, wind, radiation, air, and air contaminants.

Biologic factors. Attack of a material by a living organism, such as bacteria or insect infestation.

Stress factors. Loads on a system, either sustained or periodic. For example, stress may result from gravity loads, thermal loads, shrinkage, swelling, or settlement.

Incompatibility factors. Chemical reactions, such as chloride attack of steel, or physical interactions between materials, such as abrasion.

Use factors. Wear and tear associated with construction and service or application of loads that exceed the strength of the system.

Table 1.1 illustrates the variety of factors that can influence the service life of building components. In many instances, degradation factors work in tandem; for example, corrosion of steel is a chemical attack (incompatibility factor), but it usually occurs in the presence of water (a weathering factor).

The time dependence of deterioration mechanisms is variable. In general, the development rate may increase, decrease, or remain roughly constant over time. Decreasing-rate mechanisms, such as shrinkage of concrete, will diminish in rate of deterioration over time, even though the cumulative deterioration is always increasing in magnitude. Increasing-rate mechanisms will develop faster over time, typically because the deterioration “feeds” on itself; for example, the erosion of the concrete shown in Fig. 1.3 facilitates ponding of additional water, thereby accelerating the erosion. Constant-rate mechanisms, such as carbonation of concrete, generally proceed linearly over time.

Obviously, it is easiest to predict the future behavior of systems affected by constant-rate mechanisms. Also, decreasing-rate mechanisms tend to be fairly straightforward to deal with in condition assessments because at any time that the structure is studied the rate of future deterioration will, by definition, be diminishing. Increasing-rate mechanisms pose the hardest problem in predicting future behavior; for instance, once freeze-thaw damage becomes evident, there may be little time remaining to arrest it before complete disintegration occurs.

Below is a brief overview of the defects and types of deterioration specific to the four most common building materials: concrete, steel, wood, and masonry. More comprehensive catalogs of defects and deterioration mechanisms are provided by SEI/ASCE 11-994 and Nicastro,2 as well as in other chapters of this book.

Concrete

Defects. Concrete is a composite material; the interaction of its components leads to many of the design and construction defects common to the material. One of the principal design defects that causes distress in concrete members is improper detailing of reinforcement. The lack of proper detailing in concrete can lead to distress as minor as spalling and as catastrophic as collapse. At one point, the American Concrete Institute (ACI) estimated that repair and rehabilitation accounted for approximately 70% of the U.S. construction market.5

Other sources of concrete defects stem from errors in concrete mix design based on the numerous possible combinations of admixtures, aggregates, and cement types. Susceptibility to cracking, freeze-thaw damage, and chemical attack all can arise from poor mix design. In addition, poor quality aggregates and impurities in the mix water can affect quality adversely.

Most construction defects in cast-in-place concrete come from improper placement, curing, and finishing. A common consequence of these defects is uncontrolled crack-
### TABLE 1.1 Degradation Factors Affecting the Service Life of Building Components

<table>
<thead>
<tr>
<th>Weathering factors</th>
<th>Radiation</th>
<th>Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Nuclear</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thermal</td>
</tr>
<tr>
<td>Temperature</td>
<td>Elevated</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Depressed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cycles</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>Solid (such as snow, ice)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Liquid (such as rain, condensation, standing water)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vapor (such as high relative humidity)</td>
<td></td>
</tr>
<tr>
<td>Normal air constituents</td>
<td>Oxygen and ozone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Carbon dioxide</td>
<td></td>
</tr>
<tr>
<td>Air contaminants</td>
<td>Gases (such as oxides of nitrogen and sulfur)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mists (such as aerosols, salt, acids, and alkalis dissolved in water)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Particulates (such as sand, dust, dirt)</td>
<td></td>
</tr>
<tr>
<td>Freeze-thaw Wind</td>
<td>Microorganisms</td>
<td></td>
</tr>
<tr>
<td>Biologic factors</td>
<td>Fungi</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bacteria</td>
<td></td>
</tr>
<tr>
<td>Stress factors</td>
<td>Stress, sustained</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stress, periodic</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Physical action of water as rain, hail, sleet, and snow</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Physical action of wind</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Combination of physical action of water and wind</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Movement due to other factors, such as settlement or vehicles</td>
<td></td>
</tr>
<tr>
<td>Incompatibility factors</td>
<td>Chemical</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Physical</td>
<td></td>
</tr>
<tr>
<td>Use factors</td>
<td>Design of system</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Installation and maintenance procedures</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Normal wear-and-tear</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Abuse by the user</td>
<td></td>
</tr>
</tbody>
</table>

...ing, particularly of slabs. While concrete cracking is inevitable owing to the nature of the material, it can be limited. In addition, crack locations can be controlled when the design is detailed properly and construction is monitored. Placement and finishing, adequate control joints and expansion joints, proper curing, and adequate concrete cover and/or slab depth all are required for the prevention of unwanted cracks in concrete slabs and members.

Additional problems often arise owing to quality control during concrete placement, the most infamous of which is the on-site addition of water to the concrete mix to increase workability. Improper vibration or consolidation during placement can lead to honeycombing, delamination, stratification, and spalling, as well as a reduction in structural capacity.
Most concrete defects can be prevented through proper design and construction monitoring. A comprehensive resource for design and construction of concrete structures is the *ACI Manual of Concrete Practice.*

_Deterioration._ Much of the deterioration found in concrete stems from either the defects just discussed or the deleterious effects of water. Water is the primary catalyst for concrete weathering, scaling, erosion, bleeding, leaching, freeze-thaw damage, and chemical reactions. In some instances, incompatibility factors will not manifest distress without the addition of water (e.g., corrosion of steel reinforcement). Concrete is particularly susceptible to chemical incompatibility, including alkali-silica reactions, alkali-carbonate reactions, carbonation, and sulfate attack.

_Steel_

_Deffects._ Of the materials commonly used in construction, steel is manufactured under the most controlled conditions, and consequently, material defects are not particularly common. Most defects in steel members and structures arise from either improper design and detailing or errors in fabrication and erection. Steel defects that occur during construction typically stem from errors in erection, including misalignment of members and connections. Misalignment of members can lead to eccentric loads not accounted for in the original design. A dominant source of construction errors (and the subsequent structural distress) is improper installation of connections and/or poor-quality welding.

The cross-sectional shapes used in steel assemblages are particularly susceptible to stability failures. These failures may be on the local level (e.g., web buckling), at the
member level (e.g., lateral torsional buckling), or on a system level (e.g., story buckling). System instability is typically catastrophic in nature. This phenomenon is not limited to fully constructed facilities; it occurs more often as a result of insufficient lateral bracing during construction.

Deterioration. Deterioration of steel at the material level stems primarily from incompatibility factors, such as chemical attack, that lead to corrosion. There are a large number of ways that steel can corrode. A partial list of corrosion types includes chloride-accelerated, concentration cell, crevice, deposit, electrochemical, electrolytic, galvanic, pinpoint, and thermogalvanic. Section loss may occur due to corrosion, reducing the strength or stability of a steel member or system. Proper surface treatment of steel, such as corrosion resistant paint, often can reduce or prevent the occurrence of corrosion.

Deterioration in steel may stem from overstress conditions owing to underdesign, overload, unanticipated eccentric loads, or fatigue. These conditions may manifest plastic deformations or cracking in steel elements. Misalignment of steel members, particularly at connections, is a common cause of unanticipated eccentric loads on steel structures, which can lead to deterioration.

Wood

Defects. Wood is an organic material, and some defects are a natural part of the material; these are easily detectible during structural surveys. Wood defects generally result from growth or drying. Knots develop from branch growth, shakes are grain separations that develop between growth cycles, and checks are cracks resulting from the differential shrinkage rates of wood parallel and transverse to the grain that result from improper cutting and drying of dimension lumber. Splitting occurs in wood as a result of the same mechanism as checks. Knots, shakes, checks, and splits create local stress concentrations in structural lumber and may lead to failure.

Other defects affecting the structural integrity, as well as the aesthetics, of wood components include deformations, such as bowing, twisting, crooking, and cupping. These deformations may result from improper drying in fabrication, improper material storage, and one-sided coating applications.

Deterioration. Wood deterioration often can be attributed to deficiencies in maintenance, such as exposure to weathering factors without proper protective coatings. Leaking building envelopes, peeling paint, and damp conditions often lead to the accelerated deterioration of structural wood components.

As an organic building material, wood is especially vulnerable to biological degradation factors. Wood fibers act as a food source for a variety of organisms, such as fungus and bacteria, as well as several types of insect.

Wood rot results from a combination of conditions within a structure and functions as deterioration by consumption. A fungus breaks down the cellular structure and leaves the wood with little or no structural integrity. The various species of fungi, such as dry rot, wet rot, soft rot, and white rot, require a food source (cellulose), oxygen, water, and particular temperature, light, and pH ranges to thrive. Wood typically does not rot if it is continuously submerged in water or if it is well protected from water; however, the intermittent wetting and drying of wood provides ideal conditions for fungal attack and resulting deterioration.

In addition, softened, damp wood provides an ideal environment for several burrowing insects. Termites, carpenter ants, carpenter bees, marine borers, and various beetles consume wood fibers; loss of structural integrity and premature failure may result. Non-consumption-based degradation factors also affect wood, such as elevated humidity and moisture levels, which may reduce the strength and stiffness of wood.
Masonry

Defects. Masonry units may consist of brick, concrete (CMU), terracotta, and natural stone. Each material possesses unique criteria for design, fabrication, and installation. However, there are some characteristic defects common to all types of masonry systems.

Like concrete, masonry structures are composites; many defects in masonry systems arise from improper attention to the interface of the components. The most common structural application for masonry is exterior wall systems composed of masonry units, mortar, and reinforcement. For an exterior wall system to function, both structural (load-bearing) and environmental (weatherproofing) aspects must be addressed in the design.

Defects in the structural systems of a wall often result in increased stress factors. For example, deficiencies in the masonry units themselves, such as underfired brick, make the units more susceptible to cracking, spalling, and crushing. Improperly selected mortar, for either initial construction or repointing, may lead to crushing of the surrounding masonry due to differences in expansion. Deficient detailing of control and expansion joints may restrain normal movement of masonry and result in elevated internal stresses within the wall. Similarly, the improper detailing or installation of soft joints below shelf angles often results in unintended compressive forces and related distress within a wall. The design and placement of reinforcement and lateral anchorage are also critical in controlling the load paths within a wall system because defects can result in instability or excessive stress (Fig. 1.4). If mortar selected for pointing or repointing is more impervious to water than the masonry units, water does not evaporate as readily, which may lead to accelerated weathering.

FIGURE 1.4 Defective masonry wall tie installation (pintles, not engaging eyes).
Masonry systems are particularly susceptible to distress owing to defects in detailing of the structural and architectural elements. Defects in the weather-resisting systems often result in accelerating or initiating weathering factors and premature failure. Deficiencies in the weather resistance of the masonry units may include fabrication defects such as face-bedding sedimentary stone, porous brick masonry, or deficient terracotta glazing, all of which lead to increased water absorption. Improper detailing and installation of flashing are notorious masonry defects that result in trapped water within the wall system. Additional defects commonly found in masonry walls include improperly designed or missing flashing end dams, insufficient weep holes, mortar droppings that block weep holes, and improperly terminated flashing.

**Deterioration.** Deterioration in exterior masonry walls usually propagates at an increasing rate owing to weathering factors. Specific weather-related mechanisms include freeze-thaw damage, salt recrystallization, and embedded steel corrosion. Stress factors and incompatibility factors also contribute to accelerating the deterioration of masonry, such as cracking or crushing of masonry at lintels.

Various types of masonry units share similar deterioration mechanisms that include spalling, cracking, and delamination; these often result in increased water infiltration, as well as a reduction in structural integrity. For example, embedded steel elements may corrode in a moist environment, and the corrosion by-products result in material expansion in the form of pack rust. Pack rust may expand several times the thickness of the original steel, and the swelling induces stress in the surrounding masonry units, an effect known as rust jacking. In addition, the corrosion of embedded steel structural components results in a reduction in the structural capacity of the exterior wall. In extreme conditions, these deterioration mechanisms working in concert result in failure of the wall and tremendous economic and safety hazards. Cracking and spalling on the face of a brick can result in progressive deterioration from increased water absorption and freeze-thaw damage.

Some mortar deterioration is expected. Mortar may be considered a maintainable component with a design life of approximately 30 years, and it is expected to require condition-based maintenance such as repointing. Mortar acting as a sacrificial element accommodates most of the structural movement and absorbs most of the water. Eventually, the binders within the mortar erode or break down. Mortar deterioration is readily verifiable visually or by using a probe. Generally, loose, friable mortar or mortar that is cracking or separated from the surrounding masonry has reached the end of its service life, but the same conditions also can result from defective original construction.

**DURABILITY**

Durability is the quality of maintaining satisfactory aesthetic, economic, and functional performance for the design life of a material or system. To evaluate the design life of a material or system, it is first necessary to classify the design life of whole buildings. Table 1.2 describes five building categories based on design life. A selected design life for a building may be self-fulfilling because its materials and details are chosen to have commensurate durability. For example, designers select very different products for a modular retail building with a design life of 20 years than for a high-rise office building with a design life of over 50 years.

**Design Life**

TABLE 1.2 Categories of Building Life

<table>
<thead>
<tr>
<th>Category Description</th>
<th>Building Life</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Temporary accommodation</td>
<td>Up to 5 years</td>
<td>Facilities used during construction,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>temporary exhibition buildings</td>
</tr>
<tr>
<td>2. Short-life building</td>
<td>5 to 30 years</td>
<td>Temporary classrooms, buildings for short-life</td>
</tr>
<tr>
<td></td>
<td></td>
<td>industrial processes, modular buildings</td>
</tr>
<tr>
<td>3. Medium-life building</td>
<td>30 to 60 years</td>
<td>Most industrial buildings, retail and</td>
</tr>
<tr>
<td></td>
<td></td>
<td>warehouse buildings</td>
</tr>
<tr>
<td>4. Normal-life building</td>
<td>At least 60 years</td>
<td>New health and educational buildings, new</td>
</tr>
<tr>
<td></td>
<td></td>
<td>residential structures</td>
</tr>
<tr>
<td>5. Long-life building</td>
<td>60 to 120 years</td>
<td>Major theaters, courthouses, government and</td>
</tr>
<tr>
<td></td>
<td></td>
<td>institutional high-quality buildings</td>
</tr>
</tbody>
</table>

(equivalent to expected service life and design life used in this book) as the average amount of time that an item is estimated to function when installed new and assuming that routine maintenance is practiced.

Not every component within a structure is designed to last as long as the structure itself. Economic factors and design constraints dictate that some components and materials act as sacrificial elements (e.g., zinc coatings), some are exposed to more severe weathering (e.g., roofing), and some cannot be manufactured at a reasonable cost to last long term (e.g., paint). Table 1.3 presents examples of the design life of construction components broken into three simple categories. Components with design lives much shorter than the building’s life should be identified as replaceable, components with design lives equal to or greater than the building’s life should be identified as permanent, and components that may last with proper treatment on a scheduled or condition-based cycle for the life of the building should be identified as maintainable.

It would be useful if all building components were classified according to this type of system so that failures could be understood as “premature” versus “normal.” Currently, designers, manufacturers, and owners disagree, sometimes using all three classifications for one component. Categorizing all building products and materials affects a variety of special interests and remains a complex undertaking.

Determining the influence of a product or system on the operation of the entire structure may be useful in estimating its economically appropriate service life. White

TABLE 1.3 Categories of Component Life

<table>
<thead>
<tr>
<th>Category Description</th>
<th>Life</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Replaceable</td>
<td>Shorter life than building life; replacement can be envisioned during initial design</td>
<td>Floor finishes, mechanical components, roof membranes</td>
</tr>
<tr>
<td>2. Maintainable</td>
<td>Will last, with periodic maintenance, for the life of the building</td>
<td>Exterior wall systems, doors, and windows</td>
</tr>
<tr>
<td>3. Permanent</td>
<td>Will last for the entire life of the building with little or no maintenance</td>
<td>Foundations and main structural elements</td>
</tr>
</tbody>
</table>
developed an approach using four levels of operational influence of a system to evaluate its service life:

*Highly critical.* Failure would cause the use of the facility to stop during repairs.

*Critical.* Failure would reduce efficiency, and repairs would have to be performed outside of normal operating hours.

*Not critical.* Failure would require remedial work, but it may be scheduled for convenience.

*Not affecting the structure.* Failure (typically of ancillary components) would not affect operations.

Schmalz and Steimer\(^\text{15}\) presented a classification method (after Stillman\(^\text{16}\)) in which failure modes are classified into six levels according to safety and economic factors:

1. Danger to life
2. Danger to health
3. Costly repair
4. Frequent repair repeat
5. Interruption of building use
6. No exceptional problems

To both of these classifications one could add another important criterion—whether deferring repairs would result in greater cost later, not due to inflation but rather due to an increasing-rate mechanism. For example, postponing repair of freeze-thaw damage can greatly expand the scope of future remedial work. Postponing remedy of the ponding condition shown in Fig. 1.5 will lead to premature failure of the roof membrane, requiring expensive roof replacement.

Most building components require at least maintenance, if not replacement, during the service life of a building under normal environmental loads. The “weakest link in the chain” may compromise all others if not addressed properly. For example, neglecting to replace deteriorated sealant joints may lead to the premature failure of adjacent components, such as masonry freeze-thaw damage, wood rot, and structural steel corrosion.

Systems whose failure would pose a threat to public safety or building use require a longer design life than those that pose little safety or economic threat. Table 1.4 lists the typical design life of representative building components, compiled from several publications.\(^\text{15,17,25}\)

**Service Life**

Determining the durability of components exposed to weather, pollution, natural disasters, human error, and the general wear and tear from use is a complex task. The service life of a structure also depends on human factors, such as the changing needs of property owners and communities, changing aesthetic values, and changing economic and political climates. Consequently, the design life of a structure and its actual service life both vary and may not be defined completely.

Whether a component is designed and classified to last only a short time or for the entire life of the building, premature failure occurs when the actual service life is shorter than reasonably expected. Premature failures typically are caused by defects or improper maintenance that allows for uncontrolled deterioration.

FIGURE 1.5 Severe ponding on a roof, which inevitably will lead to membrane failure if not remedied.

TABLE 1.4 Examples of Building Component Design Life

<table>
<thead>
<tr>
<th>Building System</th>
<th>Typical Design Life (in years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foundation</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Structure</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Exposed parking decks</td>
<td>30</td>
</tr>
<tr>
<td>Brick units in masonry</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Mortar in masonry</td>
<td>25</td>
</tr>
<tr>
<td>Wood siding</td>
<td>20–40</td>
</tr>
<tr>
<td>Doors</td>
<td>25</td>
</tr>
<tr>
<td>Windows</td>
<td>20–40</td>
</tr>
<tr>
<td>Asphalt shingles</td>
<td>15–30</td>
</tr>
<tr>
<td>Roof membrane</td>
<td>10–30</td>
</tr>
<tr>
<td>Finishes</td>
<td>7–20</td>
</tr>
<tr>
<td>Floor covering</td>
<td>5–10</td>
</tr>
<tr>
<td>Suspended ceilings</td>
<td>10–20</td>
</tr>
<tr>
<td>Concealed flashing</td>
<td>40</td>
</tr>
</tbody>
</table>
DEFECTS, DETERIORATION, AND DURABILITY

a subjective estimate based on observations, average estimates of similar items, or a combination thereof, of the remaining time that an item, component, or system is able to function in accordance with its intended purpose before needing replacement. Such period of time is affected by the initial quality of the item, the quality of the initial installation, the quality and amount of preventive maintenance exercised, climatic conditions, extent of use, etc.

**Estimating Durability and Design Life**

At present, there is no standardized measure of the actual durability of most construction products; therefore, a professional performing a condition assessment must use a combination of personal experience and published literature to evaluate material failures in the field. Information regarding the design life and durability of building products can be obtained from a variety of sources, including professional and technical society guidelines, manufacturers’ technical literature, published test results from recognized laboratories, published case histories and journal articles, and experience of the designer and his or her colleagues.

**Standards.** Professional and technical societies often provide unbiased industry standards written by committee and published with the consensus of designers, manufacturers, and contractors. Such standards improve communication between producers and consumers regarding the suitability and durability of building components. Using published standards, different claims made by manufacturers may be evaluated with more confidence.

Recent research regarding the service life of buildings indicates the need for more standards regarding the durability of materials, components, and systems. Manufacturers often provide conflicting and unclear information regarding the durability of the materials and components they market. Further, the more complex interaction of several products within a system also must be considered and possibly standardized to ensure reliable performance and to facilitate identification of deficiencies.

In 1988, the European Union stated the goal of increasing public health through better building practices. This EU directive motivated the British Standards Institute (BSI) to draft a standard, “Durability Requirements for Products,” presenting categories of design life for various construction systems. Some results of the BSI study are included in the tables of this chapter.

Similarly, ASTM International has published several diverse standards in recent years regarding the durability of building materials and products, including


ASTM F793: “Standard Classification of Wallcovering by Durability Characteristics.”

**Manufacturer’s Technical Literature.** Unfortunately, many building products continue to lack clear standards for durability. Information provided by manufacturers is a blend of marketing and science, often with no clear distinction between the two. Many manufacturers do not address product design life directly in their literature; they may only mention how long the product line has been on the market. Sometimes the only indicator of design life is the guarantee period provided by the manufacturer.
However, guarantees usually limit the liability of the manufacturer in the case of premature failure of the component. Liability is often difficult to isolate when products fail because proper product selection by the designer and proper installation by the contractor are beyond the control of the manufacturer. This sharing of liability often reduces the direct accountability of the manufacturer, and the written guarantees reflect these limits.

Special attention should be paid to the language in the manufacturer’s literature to ensure that the expectations of the owner can be met. Some owners may assume mistakenly that a guarantee is a maintenance agreement or insurance policy. In fact, most guarantees severely restrict the legal remedies available to the owner and do not cover incidental or consequential damages, loss of profits, or inconvenience.

Manufacturers’ guarantee periods alone do not always provide reliable information regarding product durability. They are established by manufacturers based on several factors, including the length of time a product has been on the market (longer with proven success), longer durability from product improvements, the guarantee periods set by competitors, and the product’s performance under accelerated wear and weathering tests.

**Accelerated Testing.** Durability often is quantified by the performance of a material under an accelerated weathering test. In such a test, the material of interest is subjected to magnified environmental loads. These harsh conditions applied over a relatively short test period are extrapolated to predict the behavior of the material under normal weathering for a longer period of time. The *acceleration factor* is the ratio between the test period and the associated real service time. Therefore, the exposure time until material failure during an accelerated weathering test multiplied by the acceleration factor yields the theoretical design life of the material.

While such data may be very useful in predicting the durability of components, accelerated testing remains highly subjective. Testing may not reproduce all the ancillary environmental loads contributing to deterioration of a material, such as the effects of atmospheric pollution or biologic attack. In addition, there is no industry consensus on the true acceleration factor for the most commonly used artificial weathering devices.

Even given reliable acceleration factors for such equipment, there remains variation in the repeatability and reproducibility of accelerated weathering tests. In addition, many standardized test methods do not set criteria to determine when the test subject has “failed”; they only recommend a standard practice for conducting the testing. Therefore, several precautions are necessary to produce meaningful results using accelerated weathering techniques.

A reliable accelerated testing program would correlate the results of laboratory testing to conditions observed in the field or to a control specimen exposed to non-accelerated weathering. It is also important to define the scope of the testing, with more limited or targeted testing likely to achieve more meaningful results. For example, some chemical product manufacturers will perform testing to determine whether their product is likely to stain specific adjacent materials at the site.

An example of a broader and more difficult scope of testing may be to determine the durability of a specific paint for use on the exterior of a building. The substrate, environmental exposure, and watertightness of the walls comprising the painted surfaces will affect the performance of the product in service. These additional factors must be considered in developing a meaningful accelerated weathering test.

The various combinations of different degradation factors must be taken into account so that laboratory test results can represent adequately the environmental loads that govern the in-service performance of a material. Identifying the factors most likely to affect a building component for a given installation may serve to exclude certain products from use prior to testing. The nature of accelerated testing is such that only
one or two environmental loads are magnified at a time. Therefore, complex interactions affecting a material may not be captured adequately in a laboratory test alone.

According to ASTM E632, the following steps are necessary to produce meaningful results from accelerated testing:

1. Identify the attributes and properties critical to the service life of a material or component.
2. Identify the type and range of degradation factors affecting the test subject in service.
3. Identify likely failure mechanisms.
4. Select various test methods.
5. Define performance requirements and the scope of the testing program.
6. Perform pretesting to refine the test methodology.
7. Perform the predictive service life test.
8. Correlate accelerated test data with in-service test data or observations.

Human Perceptions of Durability

Another complication to predicting durability is that there is no industry consensus on what constitutes the end of service, or failure point, for many construction products. For example, some exterior seals begin degrading owing to environmental exposure soon after they are installed; even with proper design and installation, they degrade continuously until at some arbitrary point it is determined that they must be replaced. Before replacement is implemented, some owners will allow the seals to degrade further than other owners, perhaps allowing water infiltration to become pervasive before replacing the seals. An owner’s definition of the end of service life may depend on internal policies and tolerance for deterioration.

In addition, expectations for durability vary between communities, and certain prevailing weather conditions affect durability as well. For example, solar radiation causes more rapid deterioration of components in the southern regions of the United States than in the northern regions; therefore, faded paint may be more accepted in some southern communities, whereas such deterioration may be dubbed a failure in the North. The quality of “average” and “acceptable” workmanship and building condition varies between communities as well.

Economics play a critical role in the durability of structures. Most owners consider the design life in planning capital improvement programs, which factor into the calculation of life-cycle costs. On purely economic criteria, the lowest life-cycle cost is usually the best choice among multiple options. Owners often choose to implement capital projects with short life expectancies simply because they lack one important piece of information: They do not have a basis for evaluating actual product durability.

Improvements in Durability

History has proven that if a building is designed, constructed, and maintained properly, it may remain in service for centuries or longer. Unfortunately, deferred maintenance and defects in design, fabrication, and construction often lead to premature failures and shortened service lives for many buildings throughout the United States.

According to the U.S. Census Bureau, over $13.6 billion was spent in 1992 to repair private, nonresidential buildings less than 25 years old, including $7.3 billion spent on buildings less than 15 years old. An additional $1.11 billion was spent in demolition. When comparing these figures with the reported total of $90.6 billion spent on new construction, demolition and repair of relatively young buildings represent a significant portion.
The quality of modern American design and construction was addressed in a report published by the U.S. government in November 1995 entitled, *National Planning for Construction and Building R&D*. According to this report, building defects and uncontrolled deterioration often correlate with poor indoor air quality and occupant discomfort. In addition to health consequences, the U.S. report estimated that half the world’s energy is spent in the construction and operation of buildings; therefore, improving the durability and service life of structures requires attention. Several of the cited goals focus on the elimination of design and construction defects that often lead to poor serviceability, poor indoor air quality, and premature failure of materials, components, and systems. In addition, proper maintenance, repair, and rehabilitation of existing construction (as opposed to demolition) were identified in the report as a viable means of achieving less pollution and waste. The report noted that construction waste from demolition and new construction occupies 20% to 30% of all landfill space.

**MAINTENANCE**

Even without the presence of design, fabrication, or construction defects, some components will require maintenance to control natural deterioration. The term *maintenance* has been used historically to describe vastly different procedures, including repairing concrete spalls on precast concrete cladding panels, replacing sealant joints, and underpinning a foundation. Of these examples, only repairing concrete spalls is the type of intervention that is envisioned when a component is termed *maintainable*.

It is reasonable that it will be necessary during the design life of a concrete facade to perform some condition-based maintenance. Underpinning, however, is necessary only when the foundation, a “permanent” component, suffers premature failure. Sealants are not maintainable components and instead are categorized as “replaceable” at the end of their service life. These different operations imply different uses of the word *maintenance*. Therefore, it is useful to define categories of reasonable maintenance types. BSI defined three categories of maintenance, as shown in Table 1.5.

When maintenance is not performed as required by the condition of components, it is commonly termed *deferred* maintenance. Uncontrolled deterioration and premature failure often result from such deferment, which then becomes neglect.

**ACCEPTING UNDESIRABLE EXISTING CONDITIONS**

In the design of new structures, prescriptive codes and specifications set minimum standards for design. When the condition of existing structures is assessed it is not always feasible (or even technically sound) to apply design equations or design stan-

<table>
<thead>
<tr>
<th>TABLE 1.5</th>
<th>Maintenance Levels$^{18}$</th>
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<tbody>
<tr>
<td><strong>Level Description</strong></td>
<td><strong>Scope</strong></td>
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<tr>
<td>1. Corrective maintenance</td>
<td>Maintenance restricted to restoring items to their original function after a failure</td>
</tr>
<tr>
<td>2. Scheduled maintenance</td>
<td>Maintenance at predetermined time intervals, regular cycle</td>
</tr>
<tr>
<td>3. Condition-based maintenance</td>
<td>Maintenance as a result of distress</td>
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Because building codes generally do not provide guidance on the analysis of existing structures, it is often necessary to apply engineering judgment to determine whether an existing condition is acceptable, safe, or serviceable.

When engineers are asked about comfort level regarding a calculated overload condition on an existing structure, many consider 5% to 10% overstress acceptable. They understand that a factor of safety was built into the original design, that there are practical limits to the accuracy of such calculations, that the actual live and dead loads may be well defined (as opposed to the estimates used before construction), and that being overly conservative could result in substantial economic waste (unnecessarily repairing structures that are expected to function satisfactorily). However, no published code recognizes this distinction between design calculations for new construction and analysis of existing components; an engineer may be accused of negligence for accepting such an overstress condition owing to a lack of published support for the rationale, despite sound engineering judgment.

A new code currently in development, the International Existing Building Code (IEBC), was intended originally to become the primary code for work in existing buildings, and provisions regulating repair, alterations, additions, and change of occupancy in the International Building Code (IBC) were to be deleted. It remains to be seen whether the final edition will recognize that the criteria for new construction may be overly conservative for evaluating existing construction.

It is even more difficult to standardize acceptance of distressed conditions. Design rules are based on the behavior of new materials in their original configuration. For example, while concrete design requires the engineer to consider time-dependent effects such as creep, the code equations do not take into account reduction in strength or service life owing to deterioration or delamination.

There are many questions involved in accepting undesirable existing conditions. Is the public served by remedying an existing condition to strict compliance with design standards and building codes? Does it pose an unreasonable financial burden to improve a structure that may be "good enough" but is not in strict compliance? Does the current condition of the structural element or system fall within the assumptions used to develop the code equation? In particular, the last question requires that the engineer not only understand the basis for the code equation but also use substantial judgment in determining whether the existing conditions are compatible with those assumptions.

GLOSSARY OF TERMS

Biologic degradation factor. A degradation factor directly associated with living organisms, including microorganisms, fungi, bacteria, and insects.

Catastrophic. Description of an unintended event resulting in loss of life, severe personal injury, or substantial property damage.

Collapse. A structural failure resulting in the total destruction of all or a portion of a structural system, with consequential damage to the nonstructural systems.

Damage. Distress to property (including building components) caused by a failure.

Deficient. Lacking some desirable element or characteristic. Deficient is used generally to describe design, fabrication, installation, and/or deterioration resulting in a defect.

Defect. The nonconformity of a component with a standard or specified characteristic. Defect is used sometimes as a synonym for failure, but the preferred meaning is to indicate only a deviation from some (perceived) standard that may, but will not necessarily, result in a failure. See also Latent defect.
Degradation. The lowering of a material’s characteristics (such as strength or integrity). Similar to decomposition but not necessarily implying an organic process. Also similar to deterioration but not necessarily time-dependent.

Degradation factor. An external factor that adversely affects the performance of building components and materials, including weathering, biologic, stress, incompatibility, and use factors. See also Environmental load.

Design life. The period of time after installation during which all properties of a material, component, or system are intended or expected to exceed the minimum acceptable values when maintained routinely.

Deterioration. The gradual adverse loss of physical or chemical properties of a material.

Distress. The individual or collective physical manifestations of a failure as perceivable problems, such as cracks, spalls, staining, or leakage.

Durability. The quality of maintaining satisfactory aesthetic, economic, and functional performance for the design life of a material or system.

Failure. An unacceptable difference between expected and observed performance; also, the termination of the ability of an item or system to perform an intended or required function. Most failures are not catastrophic.

Failure mechanism. An identifiable phenomenon that describes the process or defect by which an item or system suffers a particular type of failure.

Failure mode. A description of the general type of failure experienced by a system. A broader term than failure mechanism, encompassing fundamental behavior such as shear, tension, etc.

Flaw. A relatively small imperfection in a material or component. Note, however, that even small flaws can cause catastrophes if they occur in critical areas.

Hazard. An attribute of a component or system that presents a threat of harm, injury, damage, or loss to person or property.

Incompatibility factor. A degradation factor resulting from detrimental chemical and physical interactions between materials and components.

Maintainable. A material or component that may last with proper treatment on a scheduled or condition-based cycle for the service life of a building or structure.

Natural disaster. One of the following generally recognized phenomena of nature resulting in destruction of property and/or personal injury: fire, flood, hurricane, major storm, tornado, hail, earthquake, avalanche, or blizzard.

Permanent. Material or component with a design service life equal to that of the building or structure.

Premature failure. Failure of a material, component, or system prior to the end of its design life.

Progressive collapse. The collapse of multiple bays or floors of a structure resulting from an isolated structural failure owing to a chain reaction or “domino effect.”

Rehabilitate. Extensive maintenance intended to bring a property or building up to current acceptable condition, often involving improvements.

Renovate. Make new; remodel.

Repair. To restore an item to an acceptable condition by the renewal, replacement, or mending of distressed parts.

Replaceable. Easily exchanged building components or equipment. Usually, replaceable components have a design life that is shorter than the life of the structure they occupy.
Restore. To bring an item back to its original appearance or state.

Service life. The period of time after installation during which all properties of a material, component, or system actually exceed the minimum acceptable values when maintained routinely.

Sound. Good structural condition.

Stable. In a state of stable equilibrium, i.e., resistant to buckling or stability failure. Stable should not be used as a synonym for good condition.

Stabilize. The act or process of returning a material, component, system, or structure to a stable condition.

Stress factor. A degradation factor resulting from loads on a system, either sustained or periodic.

Use factor. A degradation factor resulting from design, installation, maintenance, wear and tear, and user abuse.

Weathering factor. A degradation factor associated with the natural environment; see also Environmental load.

REFERENCES
6. ACI (2003). Manual of Concrete Practice, American Concrete Institute, Farmington Hills, MI.