STRUCTURAL RENOVATION IN CONCRETE

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ROUTLEDGE

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Preface

In the past few decades, the deterioration of buildings and infrastructures has been occurring at an ever increasing rate. This has resulted in a worldwide need for the maintenance, repair and rehabilitation of degraded structures. To meet the needs, available knowledge and technologies must be collected, organized and disseminated to engineers and practitioners. Poor understanding of the deterioration problem and the inability to adopt proper remediation approaches not only lead to a waste of natural resources, but also have a negative impact on the economy of the whole world.

The maintenance, repair and rehabilitation of concrete structures involve several broad issues which encompass technical, social, and economic aspects, such as the fundamental knowledge of materials and structures as well as basic understanding of economy and sociology. In this book, we focus on the technical aspects. From material and structural points of view, a project for maintenance, repair and rehabilitation of a concrete structure usually requires knowledge and expertise in the areas of structural materials, repair materials, structural inspection, material testing, repair and/or strengthening techniques. To the best of the authors' knowledge, a book that systematically covers all these issues is currently not available. The present book can be considered the first attempt to fill such a void.

The book is divided into six chapters. Chapter 1 gives a brief introduction to renovation engineering. Chapter 2 explores the causes of deterioration of concrete structures, covering durability issues and disaster factors. Chapter 3 discusses the techniques of inspection, including destructive and non-destructive methods. Chapter 4 focuses on the traditional repair and strengthening methods such as crack repair. Chapter 5 covers the application of glass fiber reinforced plastics components for bridge deck replacement, and presents the fundamental mechanics essential for component analysis and design. Chapter 6 provides updated knowledge on the strengthening of concrete structures with fiber reinforced polymers.

The book is designed and written primarily to meet the teaching needs for undergraduate students at senior level and graduate students at entry level. It can also serve as a reference or a guide for professional engineers in their practice.

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1 Introduction

Renovation is a carefully designed series of activities to recover the load-carrying capability, enhance performance, and extend the service life of existing buildings and infrastructures with a satisfactory quality. Such activities include the repair, strengthening, and rehabilitation of aged or damaged structures. Renovation engineering is a combination of maintenance, inspection, and rehabilitation including repair and strengthening.

Over the past few decades, there has been considerable interest in the development of renovation techniques and renovation activities mainly due to the deterioration and durability problems of concrete structures. Many new techniques and a wealth of knowledge in renovation engineering have been developed and promulgated at various conferences, in papers, in press reports, and in class notes. This book aims to summarize the state-of-the-art knowledge in this field and form a systematic tool for teaching and practicing renovation activities.

In the past, outmoded and functionally obsolete buildings and infrastructures were normally demolished. However, in recent years the amount of repair and refurbishment of all types of structures has increased significantly. Owners, engineers and architects of structures need to consider economic aspects as well as the historical significance and long-term serviceability by choosing either demolition and rebuilding or renovation. The owners and the public often share an ethos of conservation and adaptive reuse and their preference is usually renovation rather than demolition. Moreover, as zoning and environmental regulations make it ever more difficult to construct new buildings, renovation has become the most practical course of action. Besides, recycling buildings can be viewed as a way to convert resources and reduce landfill demand (Newman 2001). Maintaining and repairing existing building stock, and repair and replacement of the infrastructure, have been a feature of the construction industry for nearly half a century, first in Europe and then in North America. It should be noted that preparation of specification for renovation work is quite different from the design of a new structure.

1.1 Building and infrastructure degradation

Recently, renovation engineering has attracted increasing international attention because of the frequent occurrence of serious degradation of buildings and infrastructures. Constructed infrastructure is essential for the development and progress of commerce and industry in modern society. The gravity of infrastructure degradation can be seen from the following facts. For example, ASCE's 2005 Report Card for America's Infrastructure assessed the condition and capacity of US public works with an overall grade of D. ASCE estimates that US$1.6 trillion is needed over a five-year period to bring the nation's infrastructure up to a good condition. As of 2003, 27.1 percent of the nation's bridges (160,570) were structurally deficient or functionally obsolete; it would cost US$9.4 billion a year for 20 years to eliminate all bridge deficiencies. According to the results of a study by the Association of State Dam Safety Officials, the total investment to bring US dams into safety compliance or to remove obsolete dams tops $30 billion. About 75 percent of schools need extensive repair or replacement and the repair bill for this is as high as $268 billion according to ASCE's 2005 Report Card for America's Infrastructure. In 1999, the European Union set a requirement that all European highways must be able to carry 44-ton vehicles. In the UK, about 40,000 bridges cannot fulfil this requirement and need to be strengthened. Building and infrastructure degradation has become a serious social and financial problem. It can be seen that the cost for infrastructure rehabilitation has become a huge burden on the national economy of the developed countries and soon it will be the same in developing countries. Structural deterioration, together with the need to increase load-carrying capacity, has created a big market for renovation engineering. In China, according to the report of the China Academy of Engineering, the loss caused by corrosion in reinforced concrete structures reached $140 billion per year.

Hence, evaluation and rehabilitation of existing infrastructures have become more and more important in the past few decades and will be more critical in the future. It is predicted that in the new century, fewer new designs and more rehabilitation work will be seen in civil engineering. More funds have to be used on inspection, maintenance, and management of existing infrastructure. More new technologies need to be developed for application in the rehabilitation of infrastructures. And, of course, there is an urgent need for a new book regarding this new branch of structural engineering.

1.2 Common causes of structural degradation

It is important to understand the basic causes and mechanisms of the various forms of deterioration that degrade construction material and infrastructure made of reinforced concrete. Only with this understanding, is it possible to undertake realistic assessments of the current condition of concrete structures, and to design and implement the appropriate renovation work.

Although deterioration of structure is usually a medium- to long-term process, the onset of deterioration and its rate may be influenced by the presence of defects which have their origin at the time of construction, or in the very early stages of the life of the structure (Kay 1992). Structural degradation can be divided into the following categories: (1) progressive structural failure, e.g. collapse of bridges due to repeated traffic loading and gravity loading; (2) sudden damage due to extreme loading such as fire, high speed wind or earthquake; (3) serviceability deficiencies, e.g. excessive deflections and vibrations; and (4) materials degradation, i.e. slow interaction with the environment. Deterioration of concrete can be caused by chemical attack from external sources or between the internal materials of which the structure is built, or by physical deterioration due to climatic changes, abrasion, fire, impact, explosion, earthquake, foundation failure or overloading. Specifically, the common causes responsible for structural degradations are:

- repeated loading, including:
  - traffic loading on bridges and highways;
  - wind-induced vibrations in bridges/buildings;
  - machine-induced vibrations in industrial plants;
- overloading:
  - heavy materials and equipment on floors designed for light live loading;
  - change of use resulting in higher loading than was allowed for in the original design;
- non-uniform dimensional changes:
  - shrinkage of constrained concrete;
  - differential thermal expansion of layered system (e.g. asphaltic pavement on a bridge deck);
  - expansion of internal phases (e.g. rusting steel in concrete);
- severe loading or unexpected hazards:
  - earthquake;
  - hurricane;
  - impact;
  - explosion;
  - fire which can result in some weakening of parts of the structure, as well as physical damage to columns, beams, slabs, etc.;
- loss of foundation support:
  - scouring at bridge piers which may topple after loss of support;
  - cyclic desiccation and re-hydration of clay soil;

- soil pumping under concrete pavement, with a poorly designed sub-base layer;

- abrasion/erosion of concrete surfaces:
  - wear of pavement surface by tires of trucks;
  - abrasion caused by steel-wheeled trolleys;
  - abrasion of a floor slab in a factory;
  - abrasion of marine structures by sand and shingle;
  - erosion of hydraulic structures;

- external chemical attacks:
  - acid rain;
  - sulfate attack;
  - chloride diffusion;

- internal chemical attack:
  - corrosion of reinforcing steel;
  - alkali–aggregate reaction;
  - stress corrosion coupled with chemical/stress effect;
  - phase changes;

- indirect effects of bacteria:
  - in warm temperatures, bacteria in sewage can convert sulfur compounds into sulfuric acid. Deterioration of metallic and concrete sewage pipes can then occur.

Besides these causes due to serviceability, structural deficiency can also result from errors in design and defects in construction. It is noted that a significant proportion of the problems associated with concrete structures can be traced back to design or to construction defects (Rasheeduzzafar *et al.* 1989). For instance, a design consideration of inadequate concrete cover may maximize the chance of oxygen and moisture penetrating the reinforcement, thus increasing the chance of corrosion. As far as construction is concerned, one main problem is oversight of curing and this causes early age cracking that permits external agencies, such as air and moisture, to enter the concrete and attack the cement matrix and the reinforcement. Other common construction errors may include failure to place the reinforcement in the right position, and failure to provide sufficient cover for the reinforcement, or inadequate compaction for concrete. These common flaws, occurring in design, construction and serviceability, of structural degradation may cause the following defects in the structure (Chandler 1991, p. 21):

- excess deflection in beams and floors due to weak design/unforeseen loading;

- inadequate/insufficient fixing between precast and in-situ concrete components;
- lack of sufficient load-carrying packing between precast units;
- misalignment of precast concrete panels;
- inadequate movement joints between claddings and structure;
- inadequate insulation leading to internal condensation;
- surface finishes spalling or flaking;
- distortion of wall panels.

1.3 The objectives and scope of renovation engineering

Renovation is a process of substantial repair or alteration that extends a building's useful life (Newman 2001). Renovation engineering is a very young subject in civil engineering for concrete structures. The missions of renovation engineering are:

1. to develop a better understanding of the degradation process by identifying major parameters governing the deterioration process;
2. to develop effective structural evaluation techniques; these techniques should be non-destructive in nature, fast and reliable;
3. to develop economic, functional, and effective repair, strengthening, and rehabilitation techniques;
4. to develop reliable maintenance procedures;
5. to develop the codes and specifications for repair and rehabilitation so that public safety and health are not jeopardized.

Unfortunately, systematic studies on structural renovation of concrete are scarce and there are only a few textbooks. Other limited information has been presented only in journal papers, or special conference proceedings. So far there are no comprehensive textbooks available addressing issues on renovation of concrete structures. A confluence of several factors usually establishes the need for building renovation. Some of the common ones are:

1. change in use;
2. upgrading of mechanical and electrical systems;
3. deterioration of building envelope;
4. structural damage and failure;
5. upgrading of buildings for lateral loads;
6. reducing serviceability problems.

Renovation engineering normally covers various technologies related to: (1) repair of degraded structures to recover initial load-carrying capacity; and (2) strengthening of structures to increase load-carrying capacity for current needs. The proper renovation of structures requires: (1) a good understanding of the degradation mechanisms for proper action to be taken and to avoid the recurrence of problem in the future, such as rusting when placing steel to strengthen the concrete; (2) reliable evaluation techniques for the existing condition, including a framework for structural appraisal and maintenance and non-destructive testing methods; (3) effective techniques for repair/strengthening with practical guidelines and specifications.

The focus of this book will be on the rehabilitation of concrete structures, on materials and structural aspects, not on architectural features and not on utilities, and less on interactions with other engineers. On the other hand, renovation engineering is more material-oriented. Deterioration problems are basically a materials problem, especially for concrete structures. Only in the final stage of progressive failure do structural problems become significant. Renovation engineering is very practical and requires heavy field work. Inspection and field evaluation are very important in preparing the renovation work since they provide the current condition of the structure and the suggestion for remedial work for the structure. So far, not many specifications and design codes are available for renovation. Though the specific renovation work depends on the type of the structure and its condition, the following steps are generally required for a renovation job:

1 decision on the details of the investigation;
2 investigation (preliminary and detailed) of the structure;
3 diagnosis of the causes of the deterioration and evaluation of the overall condition of the structure;
4 preparation of report to the client to suggest either renovation or rebuild;
5 if renovation is recommended, preparation of specification and contract documents;
6 conducting the designed renovation work;
7 inspection of the renovation work;
8 regular post-contract inspection and monitoring and advising on a practical program of maintenance.

1.4 Useful definitions

The following common definitions are used for various terms in this book:

Assessment – Systematic collection and analysis of data, evaluation, and recommendations regarding the portions of an existing structure which would be affected by its proposed use (ASCE 2000).

Evaluation – The process of determining the structural adequacy or the infrastructure or component for its intended use and/or performance. Evaluation, by its nature, implies the use of personal and subjective judgment by those functioning in the capacity of experts (ASCE 2000).

Infrastructure – In general, the basic economic, social, or military facilities and installations of a community, including highways, bridges, parking lots, dams and tunnels (ASCE 2000).

Inspection – The activity of examining, measuring, testing, gauging, and using other procedures to ascertain the quality or state, detect errors, defects, or deterioration and otherwise appraise materials, components, systems, or environments (ASCE 2000).

Rehabilitation – The process of repairing or modifying a system to a desired condition. It is an upgrade (of a damaged structure) required to meet the present needs; it implies sensitivity to building features and a sympathetic matching of original construction (Newman 2001).

Repair – To replace or correct deteriorated, damaged, or faulty materials, components, or elements of a system to regain strength, density and durability.

Restoration – The process of re-establishing the materials, form, and appearance of a system to those of a particular era of the system.

Retrofitting – The process of increasing the load-resistance capacity or improving the performance of a structure or portion of the structure. (An example of performance improvement is to retrofit a damper into a structure to reduce its vibration.)

2 Degradation of reinforced concrete structures

Concrete is the most widely used construction material in the world, up to 10 billion tons per year worldwide consumption. Deterioration of concrete structure has become a world-wide problem and a huge burden on human society and the economy. For instance, in the UK, £500m is spent on concrete repair per year. In the USA, US$300–400m dollars are needed for the renovation of bridges and car parks alone where de-icing slats are commonly used in practice and cause severe concrete deterioration and steel corrosion. In China, the annual economic loss due to corrosion in concrete structures has reached 100 billion RMB. Deterioration is any adverse change of normal, mechanical, physical, and chemical properties either in the surface or in the body of concrete, generally due to the disintegration of its components. Degradation processes of concrete usually start from the materials level and then proceed to the structural level. They can be classified as *physical* (caused by natural thermal variations such as freeze–thaw cycles) *artificial* (such as those produced by fires), or by *natural disasters* (such as earthquakes and typhoon), by *abrasion* (erosion), *chemical* (attack by acids, sulfates, ammonium and magnesium ions, pure water, salts or alkali–aggregate reactions), *biological* (fouling, biogenic attack), and *mechanical* (impact, explosion, overloading, settlement, cyclic loading) (Bertolini *et al.* 2004).

In practice, these processes may occur simultaneously, which makes things even worse. Among various degradation causes, steel corrosion is found to be the most severe problem for reinforced concrete structures that can create cracks, cause concrete cover spalling, reduce the effective cross-section area of reinforcement, and lead to collapse. The corrosion of reinforcing steel can be induced either by carbonation or chloride diffusion. Degradation of concrete occurring within the first hours to months after casting can do significant damage to mature concrete structures. As we know, cast in-situ concrete structures are hardly ever built under ideal conditions so defects may occur as the concrete is being cast or very soon afterwards, such as early-age cracking due to plastic settlement, plastic or drying shrinkage, creep, or thermal shrinkage. These defects permit the atmosphere and other environmental agencies to penetrate the body of the concrete and to take part in the chemical and physical processes which give rise to deterioration. There are three basic visual symptoms of deterioration in a concrete structure – cracking, spalling, and disintegration, each occurring in several different forms (Mailvaganam 1992). In a given concrete structure, the three basic indicators of deterioration may occur not only in combination, but also with several forms of each symptom being manifested simultaneously. Before any rehabilitation and renovation work can be done, the cause of the damage must be identified as clearly as possible. As far as concrete structures are concerned, degradation of reinforced concrete structures can be caused by many factors, including non-uniform dimensional changes, repeated loading, lack of durability, natural or human disasters such as typhoon, earthquake, and fire.

2.1 Degradation caused by non-uniform dimensional changes

Deformation in concrete occurs mainly as the material's response to the external load and environment. When freshly hardened concrete is exposed to the ambient temperature and humidity, it generally undergoes thermal shrinkage (shrinkage strain associated with cooling), chemical shrinkage (shrinkage associated with hydration product formation), and drying shrinkage (shrinkage strain associated with moisture loss). When the shrinkage strain is restrained, tensile stress will be built up in structural members. The degradation caused by non-uniform dimensional changes is usually associated with the difference in thermal expansion and volumetric instability of concrete. Normal concrete is very liable to dimensional changes as internal and external conditions change. This situation arises because concrete responds to both temperature and humidity effects and is almost always in a state of dynamic disequilibrium with its environments. Those dimensional changes which may be important in concrete are: (1) thermal expansion; (2) bleeding; (3) plastic shrinkage in fresh concrete; (4) drying shrinkage and cyclic swelling and shrinkage; and (5) creep.

2.1.1 Influence of non-uniform thermal expansion

Non-uniform thermal expansion can be caused by the material's different coefficients of the thermal expansion under the same heating conditions or similar materials under different thermal conditions. The coefficient of linear thermal expansion is a measure of the length change occurring in a material when it is subjected to a temperature change. Let us take a bridge deck heated by the sun as an example (Figure 2.1). During the heating process, the temperature at the top of pavement rises much faster than that at the bottom, resulting in a tendency for the pavement to bend upwards. Consequently, the concrete deck restrains the upward movement, which leads to interfacial shear stresses. However, the process is reversed during

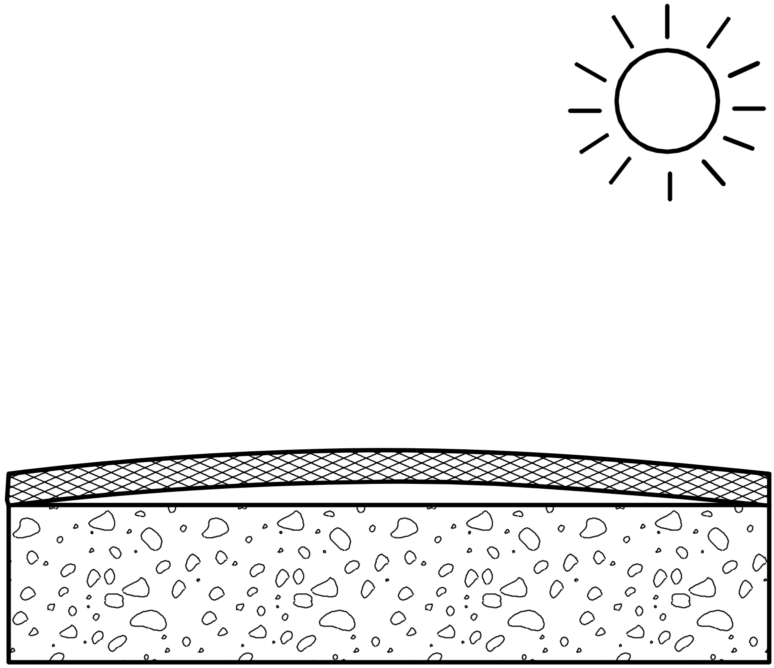

Figure 2.1 A bridge deck heated by the sun.

the cooling process. Due to creep, only part of the deformation is recoverable. Thus, under repeated heating/cooling processes, the pavement may finally debond from the deck and buckle. Traffic loading may also enlarge the debonded region and, eventually, the debonded and hence unsupported part of pavement cracks under traffic loading.

Another example of uneven thermal expansion is thermal effects generated during the hydration process of concrete. It is well known that hydration of cement is a heat-releasing chemical reaction. The heat of hydration of cement raises the temperature of the concrete, so that the concrete is usually slightly warmer than its surroundings when it hardens, and in thick sections and with rich mixes the temperature rise may be quite considerable. For a large volume of a concrete member, the temperature distribution in the member might be quite different, higher inside and lower outside. This may cause uneven expansion or uneven dimensional changes, which could lead to cracking in concrete structures. For example, a concrete dam's surface cools down faster than the interior. When the interior cools down, it "pulls away" from the hardened exterior surface, which may result in tensile stress, thus cracks, in different layers. As a common serviceability problem, the contraction and expansion that result due to seasonal temperature fluctuations can cause preexisting cracks to open and close. In general, thermal changes which cause damages to a structure are the rapid change when the concrete surface temperature changes quickly and the temperature in the core of the member changes slowly. This condition produces a curved temperature gradient with the steepest portion of the curve at the surface. As explained at the above, the upward buckling and debonding of pavement are typical examples of distress due to thermal stresses.

Restrained thermal contraction is a fairly frequent cause of cracking, and often designers do not make adequate provision for thermal movements. Non-uniform thermal expansion is at first sight a material problem, but actually it is better considered as a structural problem. Temperature differences within a concrete structure result in differential dimensional changes. When the contraction or expansion is restrained, the resultant tensile stresses exceed the tensile strain capacity of the concrete and damage (cracking) can be built up.

2.1.2 Effects of bleeding

Fresh concrete is a fluid mixture consisting of water, cementitious materials, sand, and coarse aggregate (gravel or crushed rock). The mixture remains plastic until the development of the cement hydrates starts to be connected each other. During concrete placing, compaction and subsequent plastic state, water or moisture tend to immigrate from bottom to top due to its smaller density. Meanwhile, aggregates tend to move downwards due to the equilibrium lost. The movements of the water or moisture will be obviously blocked by large size aggregate and reinforcing steel, resulting in a water film at the lower surface of these obstacles. Eventually, some water or moisture will be able to reach the surface of the specimen and form a layer of water film there. This phenomenon is called bleeding (see Figure 2.2). The concentration of water at the boundary of large size aggregate and reinforcing steel created by bleeding will form a weak interface in concrete. The characteristics of the interface include: large size of calcium hydroxide, less calcium silicate hydroxide, more porosity, and general weak nature. Moreover,

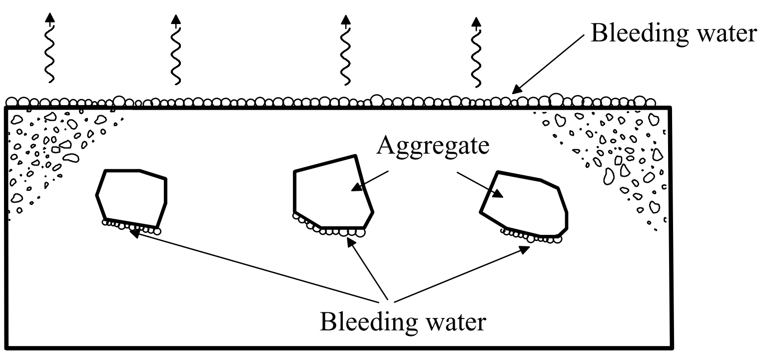

Figure 2.2 Phenomenon of water bleeding.

microcracks may form at the interface, sometimes even a microscopic crack. When cracks are formed in this way, their pattern on the surface tends to mirror that of the reinforcement. The water concentration on the surface of the specimen will result in more calcium hydroxides there, creating weak abrasion resistance on the surface.

Water also concentrates due to its upward movement when fresh concrete is compacted. Bleeding water may be trapped at the bottom of the reinforcing bar and aggregates. In the former case, the concrete may separate from the lower surfaces of the bars and a void forms due to bleeding. If this occurs in the plastic rather than the fluid state, the concrete may crack. In such a condition, the transition zone forms after hardening and unprotected steel becomes potential site for corrosion. Due to water bleeding and sedimentation (downward movement) of coarse aggregates, paste volume increases near the concrete surface and the evaporation of water eventually slows down. The fresh concrete surface then re-absorbs water to give a higher water/cement ratio and, after hardening, resistance to surface wear and abrasion is reduced. The movements associated with the reduction in volume are resisted by the concrete which lies immediately below and which is not subject to volume change. The restraint from the lower concrete causes tensile stresses to build up in the surface layer and, because the material still remains in the fresh state or plastic and has very low strength, cracking can result. Excessive bleeding can be avoided by improving the cohesiveness of the mix through reduction of water/cement ratio, using a better aggregate grading and/or increasing the cohesiveness of fresh concrete.

2.1.3 Effects of plastic shrinkage

In the fresh state, the top surfaces of concrete pours are subject to evaporation and consequent loss of the mix water. The rate of evaporation depends upon ambient conditions such as temperature, exposure to sun, wind speed and relative humidity. The water lost by evaporation is usually replaced by water rising to the surface from the bottom of the concrete by the action of bleeding.

In both cases, there are local reductions in volume when the rate of removal of water from the surface exceeds the rate at which it can be replaced by bleeding. From this point of view, a concrete mixture which provides some bleeding is helpful in reducing deterioration caused by plastic cracking. Protection of concrete surface from drying winds by the use of barriers and the earliest possible application of covering to the surface may be helpful in reducing bleeding effect. ACI 305R (1999) indicates that precautions against surface drying out and cracking should be taken if evaporation is likely to exceed 1 kg m^{-2} h^{-1}.

Shrinkage is caused by the surface tension of water within the capillary pores formed in the cement paste during evaporation. As a capillary pore starts to dry out, the remaining water forms a meniscus between the adjacent cement particles, and the forces of surface tension pull the particles together. The loss of water from concrete may cause mainly two kinds of shrinkage: plastic shrinkage and drying shrinkage. Plastic shrinkage is the phenomenon when the surface layer is hardened and starts to shrink due to water loss while the inside concrete is still wet and plastic. So, plastic shrinkage is normally caused by rapid drying of fresh concrete at the surface (Allen *et al.* 1993). The water lost by evaporation is usually replaced by water rising to the surface of the concrete by the action of bleeding as discussed in Section 2.1.2. Where the rate of water evaporation from the surface exceeds the rate at which it can be replaced by bleeding, there is local reduction in volume. The upward bleeding of water may be accompanied by a downward movement of the solid and heavier ingredients. This downward movement may be resisted by the top layer of reinforcement or by the formwork. In the former case, the layer of concrete above the reinforcement tends to become draped over the bars. If this occurs in the plastic rather than the fluid state, the concrete may crack. In addition, the concrete may separate from the lower surfaces of the bars creating a void, as shown in Figure 2.3. When cracks are formed in this way, their pattern on the surface tends to mirror that of the reinforcement. The surface profile tends to be undulating with high points over the bars. Under other conditions, the downward movement of concrete can be restrained by the shape of the formwork. Plastic shrinkage cracks tend to propagate predominantly through the matrix rather than through the aggregate (Kay 1992). The process leading to plastic shrinkage cracking is shown in Figure 2.3.

These plastic shrinkage cracks provide a path for water and other chemicals to reach the steel reinforcement, which can greatly affect the durability of concrete structures, for instance, corrosion is easily generated. In general,

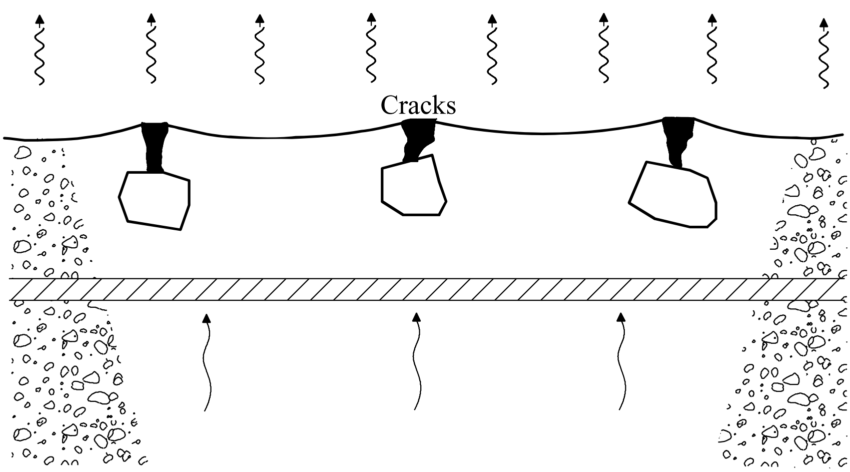

Figure 2.3 Formation of plastic shrinkage crack.

if cracks appear in an exposed concrete surface very soon after it has been finished or even before finishing is complete, they are termed "plastic shrinkage cracks" (Allen *et al.* 1993). These cracks form when wind or heat causes the concrete to lose water rapidly, usually from 30 min. to 6h after the concrete placement. They are often wide and deep and are usually discontinuous. Plastic shrinkage cracks are usually of shallow depth, generally 38–50 mm, 300–450 mm long and usually perpendicular to the wind, which cause the water loss by evaporation. Plastic shrinkage cracks typically run parallel to one another and, because of their size, they can be structurally significant. The most effective way of preventing their occurrence is by sheltering the surface from wind and sun during construction and by covering the concrete surface immediately after finishing, measures which are all directed toward reducing the rate of evaporation. BS 8110 has recommended minimum periods of curing and protection (shown in Table 2.1) for fresh concrete to reduce plastic shrinkage. Changes in concrete mix design, and especially the use of air entrainment, may also be helpful in reducing plastic shrinkage. Remedial measures after the cracks have formed usually consist of sealing them against ingress of water by brushing in cement or low-viscosity polymers (Allen *et al.* 1993).

The magnitude of plastic shrinkage may in extreme cases be as large as 10,000 microstrain (Troxell *et al.* 1968) and has been shown by L'Hermite (1960) as over 6000 microstrain for paste and 2000 microstrain for concrete. As in the plastic state, no great stress is induced in concrete and further working of the concrete can generally be applied to eliminate consequential cracks.

2.1.4 Influence of drying shrinkage

The volume change and water loss of a concrete member do not stop after its initial setting and hardening. The loss of moisture is accompanied by the reduction in volume known as shrinkage. Drying shrinkage is a slow process

Table 2.1 Minimum periods of curing and protection

Type of cement	*Ambient conditions after casting*	*Min. period of curing and protection*	
		Average concrete surface temperature	
		5 to 10 °C	*Above 10* °C
Portland cement, SRPC	Average	4 days	3 days
	Poor	6 days	4 days
All except Portland cement and SRPC, and all with GGBS or PFA	Average	6 days	4 days
	Poor	10 days	7 days
All	Good	No special requirements	

in thick members, so it may lead to a gradual build-up of tensile stress if it is restrained and, further, cracking of concrete. Cracks due to restrained shrinkage are often noticed soon after construction, but when slow drying occurs they may not be apparent until much later. The drying shrinkage crack can vary from fine hairlines to as wide as 3 mm (1/8 in.), and often serve as ports of entry for moisture, carbon dioxide, and other injurious salts (Mailvaganam 1992).

The formation of drying shrinkage can be explained as follows. In normal practice, in order to produce workable concrete, nearly twice as much water that is theoretically needed to hydrate the cement is usually added to the concrete mix. After concrete has been cured and begins to dry, the excessive water that has not reacted with the cement will begin to migrate from the interior of the concrete mass to the surface. As the moisture evaporates, the concrete volume shrinks. From cement chemistry, it is known that the drying shrinkage of concrete is caused by the contraction of the hydrated hardened calcium silicate gel during the withdrawal of water from the concrete. Even for hardened concrete, loss of water (e.g. during a hot season) can lead to drying shrinkage. The magnitude of the drying shrinkage is influenced by many factors, including:

1. the stiffness and amount of aggregate;
2. water to binder ratio;
3. the total amount of paste;
4. the types and amounts of chemical admixtures;
5. the curing regime and the age of the concrete member at which it is exposed to air;
6. the types and amounts of mineral additives;
7. the theoretical length of the concrete member that is defined as the ratio of section area of the member to its semi-perimeter in contact with the atmosphere;
8. the diameter, amount and distribution of reinforcing steel;
9. the relative humidity and its change rate;
10. the carbonation.

Among various factors, the most important ones affecting drying shrinkage are water to binder ratio and the total amount of the paste that determines the total amount of water contained in a unit volume of the concrete. Concrete with a wetter consistency will shrink more than one with a drier consistency because the former is obtained by the use of a higher water/cement ratio, by a greater quantity of paste, or by a combination of the two. The loss of moisture from the concrete varies with distance from the surface. Drying occurs most rapidly near the surface because of the short distance the water must travel to escape and more slowly from the interior of the concrete because of the increased distance from the surface. A nearly linear relationship exists between the magnitude of the shrinkage and water content of the mix for a particular value of relative humidity. Also, the shrinkage of concrete decreases as the relative humidity increases. When concrete is exposed to 100 percent relative humidity or submerged in water, it will actually increase in volume slightly as no water immigrates out. The gel continues to form because of the ideal conditions for hydration. If concrete is exposed to relative humidity less than 90 percent, it will normally shrink.

Drying shrinkage strain, ε_{sh}, is time dependent. Approximately 90 percent of the ultimate shrinkage occurs during the first year. The magnitude of the ultimate shrinkage is primarily a function of the initial water content of the concrete and the relative humidity of the surrounding environment. For plain concrete members, drying shrinkage ranges from 400 to 700 micro-strain under normal conditions. For reinforced concrete members, the shrinkage strain values are between 200 and 300 micro-strain. Because concrete adjacent to the surface of a member dries more rapidly than that in interior, shrinkage strains are initially larger near the surface than in the interior. As a result of the differential shrinkage, a set of internal self-balancing forces, i.e. compression in the interior and tension on the outside, is built up. The stresses induced by shrinkage can be explained by imagining that the cylindrical core of a concrete cylinder is separated from its outer shell and that the two sections are then free to shrink independently in proportion to their existing water content.

Since deformations must be compatible at the junction between the core and the shell, shear stresses must be created between the core and the shell. If free-body diagrams of the upper half of the cylinder are considered, it is clear that vertical equilibrium requires the shear stresses to induce compression in the core and tension in the shell. In addition to the self-balancing stresses set up by different shrinkages, the overall shrinkage creates stresses if members are restrained in the direction in which shrinkage occurs. Tensile cracking due to shrinkage will take place in any structural element restrained by its boundaries. Drying shrinkage cracks are often straight or ragged. Surface crazing on walls and slabs is an example of drying shrinkage and it is usually shallow and cosmetic in nature. Non-uniform environmental conditions produce moisture gradients which may cause differential shrinkage with resulting warping or cracking depending upon the degree of restraint experienced by the concrete – for example, curling of slabs on grade is caused by drying shrinkage and by moisture and temperature gradients.

Shrinkage must be controlled since it permits the passage of water and other chemicals, is detrimental to appearance, reduces shear strength, and exposes the reinforcement to the atmosphere. For large concrete surface, joints need to be provided to prevent such cracking. Alternatively, shrinkage compensation concrete can be used to reduce drying shrinkage. The cement, used for making shrinkage compensation concrete, contains significant amounts of calcium sulfate and calcium sulfoaluminate. On hydrating, the reaction products occupy a larger volume than the original reactants. The volume of concrete keeps increasing during the first few days. When water loss occurs later, shrinkage occurs which reduces the volume to roughly the original value. Precautions in its application include: (1) expansive reaction stiffens up the concrete rapidly; (2) at high temperatures, above 27–29 °C, slump loss and quick setting may be a problem, so ice is normally needed to reduce the temperature; (3) quick stiffening makes plastic cracking easy and extra care is required to prevent rapid evaporation.

2.1.5 Influence of creep

Creep is a continuous deformation which occurs in concrete under sustained load, and its consequences are only evident after years. Creep can thus be defined as the increase in deformation under a sustained load. The deformation increased by creep can be several times as large as the deformation under loading. Creep is thus of considerable importance in structures. Inadequate design which fails to consider the influence of creep of the structural elements of a building, for instance, shortening of columns or deflection of floors and beams, may result in load being transferred to non-structural elements such as partition walls or cladding panels. In prestressed concrete, in flat slabs and in slender members liable to instability and buckling, creep may be harmful and the advantages of low creep concrete should be considered by the designer in these circumstances.

When a sustained load is removed from a concrete member, the strain decreases immediately by an amount equal to the elastic strain at the given age, generally lower than the elastic strain on loading. This instantaneous recovery is followed by a gradual decrease in strain, called creep recovery, but the recovery of creep is not complete. Creep is not a simply reversible phenomenon, so that any sustained load results in a residual deformation. In concrete, only the hydrated cement paste undergoes creep while the aggregate is relatively hard and considered creep-free. In fact, due to its relatively high stiffness, aggregates can restrain the creep of cement paste. Therefore, creep can be considered as a nonlinear function of the volumetric content of cement paste in concrete. The volumetric content of unhydrated cement paste, the volumetric content of aggregate, the grading, maximum size, shape and texture of the aggregate and certain physical properties of aggregate will affect the magnitude of creep. Among various physical properties of concrete, the modulus of elasticity of aggregate is probably the most important factor which influences creep of concrete and the influence of other aggregate characteristics may be indirect. The higher the modulus of the aggregates, the greater the restraint provided by the aggregate to the potential creep of the hydrated cement paste. Normally aggregates with a higher porosity have a lower modulus of elasticity, thus a lower restraint to creep of concrete.

Also, the porosity of aggregate plays a direct role in the transfer of the moisture within concrete, which is closely associated with creep of concrete.

As a result, some lightweight aggregates batched in a dry condition exhibit high initial creep. What's more, the rate of creep of lightweight aggregate concrete decreases with time more slowly than in normal weight concrete. The type of cement affects the creep of concrete since cement influences the strength of the concrete at the time of application of the load. Experimental data show that within a wide range of concrete strengths, creep is inversely proportional to the strength of concrete at the time of application of load (Mehta and Monteiro 2006). Fineness of cement affects the rate of hydration and the strength development at early ages and thus influences creep. Extremely fine cements, with a specific surface up to 740 kg/m^2, lead to a higher early creep but to a lower creep after one or two years under load (Bennett and Loat 1970). Strength increases in order of: low heat, ordinary, and rapid-hardening cements, so that for a constant applied stress at a fixed (early) age, creep increases in order of rapid-hardening, ordinary, and low heat cements. Creep of concrete made with expansive cement is larger than that of concrete with Portland cement only.

The mechanism of creep in concrete can be related to thermally activated creep. It assumes that the time-dependent strains are the result of thermally activated processes that can be described by rate process theory. Creep strains will originate through deformation of a micro-volume of paste, called a "creep center". The creep center will undergo deformation to a lower energy configuration under the influence of energy added to the system by external sources. This deformation can only occur by going through an energy barrier in the form of an intermediate, high-energy state. The most prevalent view involves slip between adjacent particles of C–S–H under a shear stress. If there is a sufficient amount of water between layered C–S–H, which reduces the van der Waals' forces sufficiently, slippage is ready to occur and hence the creep. Creep can also result from the diffusion of micro water under stress (Mindess *et al.* 2003). Water-reducing and set-retarding admixtures lead to pore refinement in the hydration product and have been found to increase the basic creep in many, but not all cases (Hope *et al.* 1967; Jessop *et al.* 1967).

The environmental humidity of concrete is also an important factor influencing creep. An increase in the atmospheric humidity is expected to slow down the relative rate of moisture flow from the interior to the outer surfaces of concrete. Taking a broad view, for a given concrete, the lower the relative humidity, the higher the creep. The strength of concrete has a significant influence on creep: within a wide range, creep is inversely proportional to the strength of concrete at the time of application of the load. The size and the shape of a concrete element also have some influence on the magnitude of creep since the rate of water loss is obviously controlled by the length of the path travel by the water and the resistance of water escaping from the interior of the concrete is closely related to creep.

Other factors influencing creep include the curing history of concrete, the temperature of exposure and the applied stress. Creep strains can be significantly different when concrete elements are cured in different histories. For instance, drying cycles can enhance micro-cracking in the transition zone and thus increase creep. The exposure temperature of concrete can have two counteracting effects on creep. On the one hand, if a concrete member is exposed to a higher than normal temperature as part of the curing process before it is loaded, the strength will increase and the creep strain would be less than that of a corresponding concrete stored at a lower temperature. On the other hand, exposure to high temperature during the period under load can increase creep. As far as the applied stress is concerned, there is a direct proportionality between creep and the applied stress for hardened concrete. It appears safe to conclude that, within the range of stresses in structures in service, the proportionality between creep and stress holds good, and creep expressions assume this to be the case. Also, creep recovery is also proportional to the stress previously applied (Yue and Taerwe 1992).

Creep is usually determined by measuring the change with time in the strain of a specimen subjected to a constant stress and stored under appropriate conditions. ASTM C 512-94 describes a spring-loaded frame to measure the creep of a concrete sample which maintains a constant load on a concrete test cylinder despite any change in its length. Since creep may develop over as long as 30 years, the measurement can only cover a short period of the age of concrete. Numerous mathematical expressions relating creep and time have been suggested, among which includes the modified Ross expression of ACI 209R-92 (1994a) and those suggested by Bazant and his co-workers (1992).

Creep affects strain, deflection and, often, stress distribution. In concrete structures, creep reduces internal stresses due to non-uniform shrinkage, so that there is a reduction in cracking (Neville *et al.* 1983). In reinforced concrete columns, creep results in a gradual transfer of load from the concrete to the reinforcement. In an eccentrically loaded column, creep increases the deflection and can lead to buckling. In statically indeterminate structures, creep may relieve stress concentrations induced by shrinkage, temperature changes, and so on. However, in mass concrete, creep may cause cracking when a restrained concrete mass undergoes cyclic temperature changes. Creep can also lead to an excessive deflection of structural members and cause other serviceability problems, especially in high-rise buildings and long bridges.

2.2 Degradation caused by repeated loading

Components of reinforced concrete structures such as machine foundations and bridges are frequently subjected to repeated loading (cyclic loads), and the resulting cyclic stresses can lead to microscopic physical damage in the materials. The damage can accumulate and further lead to the strength reduction and then structural degradation. The trend of strength reduction

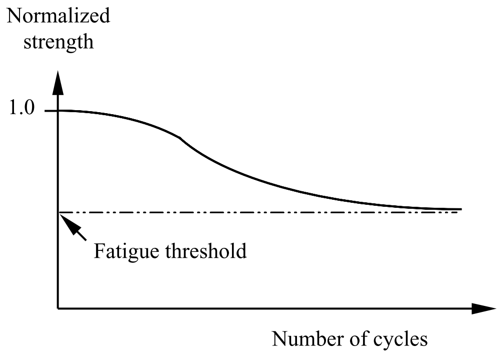

Figure 2.4 Normalized fatigue strength as a function of number of loading cycles.

can be seen from the so-called *S–N* curve as shown in Figure 2.4. The cyclic fatigue can be defined as a failure caused by a sufficient repeated application of loads that are not large enough to cause failure in a static application. This implies that some internal progressive permanent structural damage must be accumulated in the reinforced concrete structure under the repeated stress.

A typical cyclic loading is shown in Figure 2.5. Some useful definitions and basic concepts for cyclic loadings can be introduced, referring to Figure 2.5:

Constant amplitude stressing – cycling between maximum and minimum stress levels that are constant (see Figure 2.5(a));
Stress range, $\Delta\sigma$, is the difference between the maximum and the minimum values;

$$\Delta\sigma = \sigma_{\max} - \sigma_{\min} \tag{2.1}$$

Mean stress, σ_m, is the average of the maximum and minimum values;

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2} \tag{2.2}$$

Stress amplitude, σ_a, is the half of stress range;

$$\sigma_a = \frac{\Delta\sigma}{2} = \frac{\sigma_{\max} - \sigma_{\min}}{2} \tag{2.3}$$

Completely reversed stressing – mean stress equal to zero with constant amplitude;
Stress ratio, R, is $\sigma_{\min}/\sigma_{\max}$;
Amplitude ratio, A, is σ_a/σ_m

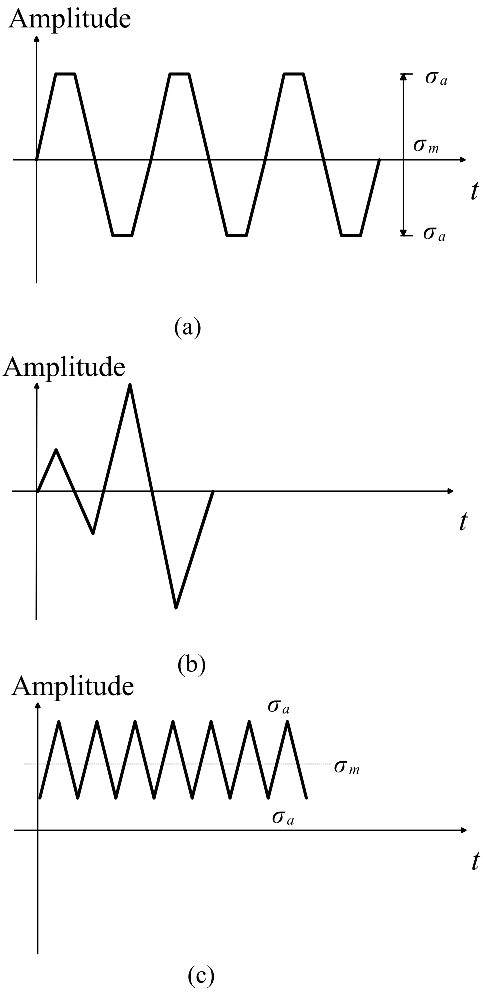

Figure 2.5 Different types of cyclic loadings.

In cyclic fatigue, the symbol "*S*" is usually used to represent nominal or average stress, which is different from the true stress at a point, σ. Nominal stress distribution is determined from the load or the moment using formulae in mechanics of materials as a matter of convenience while true stress is determined according to the real materials state (stress concentration, yielding). *S* is only equal to σ in certain situations. The fatigue strength of a material is largely influenced by the maximum stress applied, the difference between maximum and minimum stress (stress range), and the number of cyclic loading. It should be noted that for one cycle of loading and unloading, the concrete stress–strain curve is a closed cycle (see Figure 2.6). The area enclosed is proportional to hysteresis and represents the irreversible

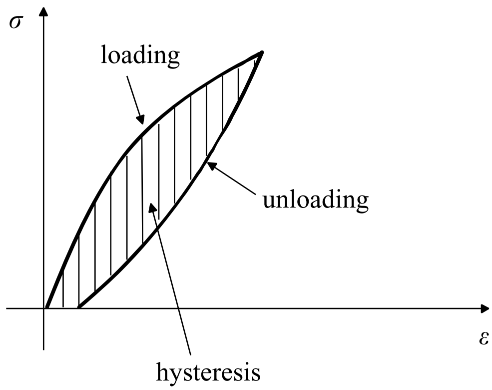

Figure 2.6 Hysteresis loop during loading and unloading.

energy of deformation, i.e. energy due to crack formation or irreversible creep.

The fatigue life of a material is usually plotted as a figure of nominal stress versus cyclic number, *S–N* diagram. To get an *S–N* diagram, fatigue tests have to be conducted. Each test deals with a fixed stress amplitude and mean stress. The test continues until the specimen fails at a cyclic number of *N*. Each experiment result will generate one point on the *S–N* diagram. The *S–N* diagram should have sufficient data points to make the empirical analysis meaningful. To make things simple, usually a completely reversed stressing, mean stress equalling to zero with constant amplitude, is adopted first to build up the *S–N* diagram. For the cases of mean stress not equalling zero, fatigue life can be estimated by using the *S–N* diagram of completely reversed stressing as stated in the following section.

When sufficient experimental data are obtained from completely reversed stressing fatigue test, the *S–N* diagram can be plotted in a linear-linear coordinates, or linear-log coordinates, or log-log coordinates. If *S–N* data are found to be a straight line on a log-log plot, the relationship between stress amplitude and fatigue cycles can be written as:

$$\sigma_{ar} = A(N_f)^B \tag{2.4}$$

where σ_{ar} is the stress amplitude for completely reversed stressing corresponding to N_f. The A and B are material constants; and N_f is the cycle to failure.

For the cases where $\sigma_m \neq 0$, the relationship between the stress amplitude where $\sigma_m \neq 0$ and the stress amplitude for completely reversed stressing can be expressed by the empirical modified Goodman law,

$$\sigma_a = \sigma_{ar}\left(1 - \frac{\sigma_m}{\sigma_\mu}\right) \tag{2.5}$$