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High-Performance Concrete and Fiber-Reinforced High-Performance Concrete under Fatigue Efforts

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Additional information is available at the end of the chapter

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Abstract

Fatigue is the process of mechanical degradation of a material, which leads to its collapse. Repeated load applications with a maximum value lower than the one that provokes the static failure of the material, causes internal damage in the material that, progressively, reduces its mechanical capacity until it finally collapses. The increasingly widespread use of high-strength concretes permits the construction of more lightweight structures. This implies that the variable loads (which are the causes of fatigue) represent an ever larger percentage of the total load. In consequence, fatigue is an increasingly important factor in concrete structures. In some cases, it even begins to be the dimensioning load of the structure. In addition, the presence of fibers within the concrete modifies the fatigue response of the concrete. In this chapter, the classic theory of fatigue is presented in detail and the most recent developments in the study of concrete fatigue are discussed.

Keywords: fatigue, high-performance concrete, fiber-reinforced high-performance concrete, degenerative process, modulus of elasticity, S-N curves

1. Introduction

1.1. Definition of fatigue. Interest in fatigue

Fatigue is a process of mechanical deterioration of a material leading to its collapse, caused by the repeated action of cyclic loading, in such a way that its maximum applied load is always below the maximum loading that a “healthy” specimen of the material could resist under static loading until failure.

The first research works on material fatigue were completed in the mid-nineteenth century during the industrial revolution. Wöhler was the first to conduct systematic fatigue studies. The first works on concrete date back to the end of the nineteenth century [1, 2].

It was at the beginning of the twentieth century when real concerns over structural fatigue began to appear in civil engineering, applied above all to metallic structures. This concern was prompted by the appearance of catastrophic failure in some structures, the explanations for which could not be solved with classic mechanics.

Fatigue is of growing interest in civil engineering, especially in concrete structures. The development of concretes with stronger mechanical properties (better resistance) means that structures may be built with less specific weight. This aspect means that variable loads of a cyclical nature (live loads, wind, etc.) are of increasing relevance (**Table 1**) [3].

Low-cycle fatigue			High-cycle fatigue				Super-high-cycle fatigue		
1	10^1	10^2	10^3	10^4	10^5	10^6	10^7	10^8	10^9
Structures subjected to earthquakes			Airport pavements and bridges	Highway and railway bridges, and highway pavements		Mass rapid transit structures	Sea structures		

Table 1. Classes of fatigue loads [3].

There has been a surge in the construction of new transport infrastructure in recent years, for the main part involving new high-speed railway lines. These new railways imply a very competitive alternative for intercity transport over medium distances.

These significant engineering works means that one of the most important structural aspects specifically associated with the design of railway bridges and structures is a topical question: the effects of fatigue due to the live loads of trains.

Standards establish a fatigue limit state, because of failure of a structural element when a crack or fissure opens as a consequence of repeated and variable stress loads, produced by the action of traffic, which is expected to continue throughout the useful life of the structure (100 years).

1.2. The fatigue process in concrete

Concrete fatigue is a progressive process of birth and growth of microcracks, which provokes a change in the mechanical properties of the matrix, a reduction in stiffness, and an increase in total deformation. And it leads to the failure of the concrete.

Unlike steel, concrete is a heterogeneous material in which nonlinear fatigue can occur which depend on its stress levels. Concrete fatigue fundamentally depends on the stress level (σ_{\max}/f_c) and not only on the stress range ($\Delta\sigma$) as happens with metals.

Research on cumulative damage due to microcracking in concrete began in 1929, when Richardet al. [4] observed that the apparent volume of concrete started to increase under compressive axial loading when it reached a value of 75–85% of the ultimate failure load. This

level of loading is referred to as critical load. The increase of the apparent volume of concrete is due to the internal microcracking.

Many authors have also analyzed fatigue behavior, observing important changes within the concrete as from 75% of the failure load. These changes are due to microcracking in the concrete, which increase its volume and its Poisson's ratio [3].

The later use of ultrasonic techniques has allowed to determine the initial moment when microcracking starts [5]. These microcracks were first recorded at values of around 25–30% of the ultimate failure load and the ultrasonic signal rapidly increased from 75%.

The failure of concrete may be defined at three levels:

(1) At a microscopic level, the bonds between the crystals of calcium silicate hydrate are taken into account. This level is less interesting from the point of view of fracture mechanics. Its behavior is regulated by physical and chemical processes that are activated under certain circumstances.

(2) At an intermediate level, the cement paste, the aggregate, and their interrelations are taken into account. The standard failure process, regardless of the type of load applied, occurs when one or more of the following are surpassed: the friction strength of the aggregate, the shear strength of the aggregate, the friction and the tangential strength of the cementitious matrix, and the friction strength of the aggregate.

Figure 1 describes the stress conditions within the aggregate:

(3) From the macroscopic point of view, concrete can be modeled as a homogenous isotropic material that contains defects in its interior. The properties that are analyzed at this level are the stress levels and the average deformation that is generated, and also the nonlinearity of the mechanical properties.

The macroscopic response (stress-strain diagram) of a concrete specimen subjected to increasing monotonous shortening is a consequence of the evolution of the material at a microscopic level. Microcracks occur because of friction stress due to the specific heterogeneity of the material. The appearance of microcracks in an orthogonal direction to the principal compressive stress direction can be due to:

- (1) Existence of pores or microcracks prior to loading.
- (2) Difference in stiffness between the aggregate particles and the cement paste.
- (3) Loss of adhesion in the aggregate-paste interface.
- (4) Sliding zones in the cement paste.

There are mainly two hypotheses that seek to clarify the onset of cracks in concrete under cyclic loads:

The first hypothesis assumes that the cyclic loading provokes cracks that subsequently progresses up until the collapse of the element.

The second hypothesis considers that microcracks has already occurred in the concrete setting and hardening process. Cyclic loads simply propagate these fissures.

In any case, microcracks have macroscopic consequences: the growth of irreversible deformation and a reduction in stiffness take place [7].

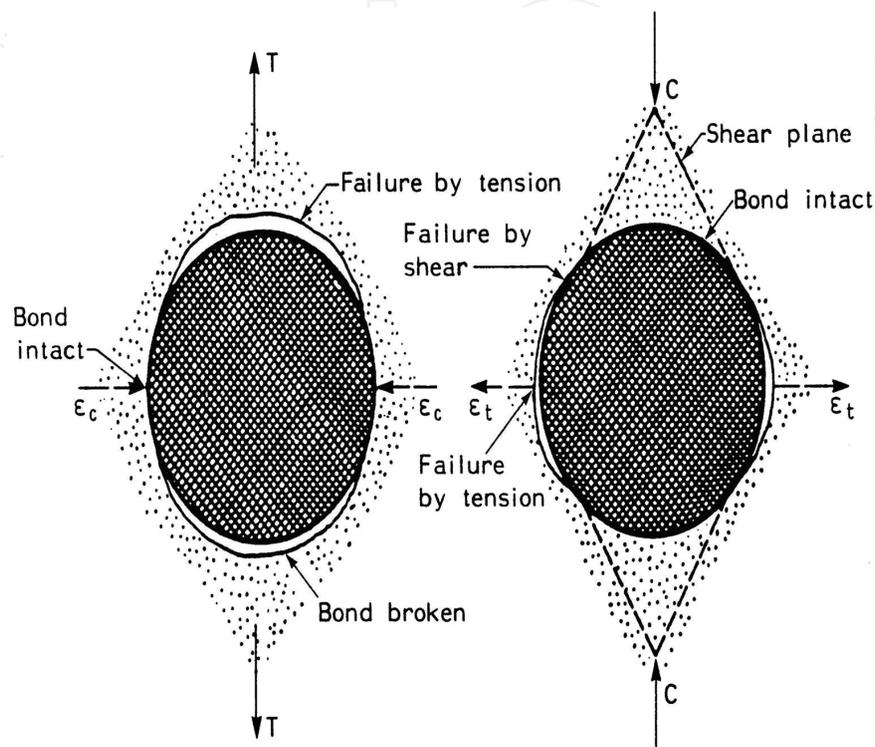


Figure 1. Local stress within the aggregate under compressive and friction stress [6].

Irreversible deformations are the sum of two effects:

1. On the one hand, part of the deformation as viscoelastic properties. Short-term viscoelastic deformation may be because of capillary flows due to thermodynamic imbalance. Long-term viscoelastic deformations are associated with the repositioning of calcium silicate hydrate within the nanopores. If these viscoelastic deformations are locally larger than the deformation capacity of the concrete, fissuring of the concrete will occur.
2. Moreover, cyclic loads cause some of the aggregates or parts of the cement paste to harden when the fissure has opened, producing localized frictional forces.

The fracture mechanics of concrete, like all petrous materials, differ from those of metals. The fracture mechanics of both concrete and steel structures is considered nonlinear due to the development of an area of significant size in which the fracture lines appear. While in metals with a fragile or ductile behavior, the hardening process in most of that area is nonlinear and presents a small fracture generation zone. In contrast, concrete presents a large fracture generation zone that is surrounded by a small nonlinear hardened zone. The concrete may therefore be considered a quasi-fragile material [8].

The cyclic loads and, therefore, the fatigue behavior of concrete may be established for compression, tension, and bending efforts. In case of plain concrete, only fatigue under compression efforts is of interest. In case of fiber-reinforced concrete elements, fatigue under tension and/or bending is of interest too.

1.2.1. Fatigue of high-strength concrete

The fatigue behavior of high-strength concrete differs from that of ordinary concrete due to the differences in its internal structure. The cracks in ordinary concrete are propagated in the cement paste through the aggregate-paste interface. However, cracks in high-strength concrete are propagated in the cement paste and in addition through the aggregates, due to the relatively higher strength of the cementitious matrix. The fatigue life of the aggregates in high-strength concrete should therefore be taken into account where its strength is important [8]. However, the tests undertaken show that the fatigue life is relatively similar for various types of concrete. The studies on fatigue show that higher concrete strength leads to greater fragility, as also happens in the behavior of concrete under monotonous loading.

2. Concept of fatigue life “N” and fatigue strength “S.” S-N curves

The conventional approach to the problem of concrete fatigue consists in determining the number of cycles N that a concrete specimen can withstand when subjected to a cyclic load, in such a way that the maximum stress that is applied is lower than the compressive strength of the material.

Concrete strength is empirically assessed through a series of tests. The basic premise, observed in all the materials, is that the lower the maximum tensile stress that is applied, the higher the number of cycles N that the material can withstand.

The value of N depends on the maximum and the minimum stress levels that are applied. The standard way of representing these extremes is relative maximum stress ($S_{c,max} = \sigma_{c,max}/f_c$) in relation to the number of cycles (N), drawing different graphs for different values of minimum relative stress ($S_{c,min} = \sigma_{c,min}/f_c$). These are referred to as the S-N curves (**Figure 2**).

Fatigue strength S is defined as the fraction of static strength that can be withstood in a repeated manner over a certain number of cycles.

The definition of an S-N curve requires many tests. A set of specimens is used to characterize a material and they are subjected to variable forces at different stress levels, measuring the number of cycles that it withstands until failure. In general, there is enormous dispersion in the results of apparently similar specimens. These differences are due to the dispersion of concrete strength [10]. In general, it is necessary to test a large number of specimens for each stress level, before reliable results may be obtained [11].

Many of the S-N fatigue curves shown in the literature were obtained by using different test setups, specimen types and shapes, etc. At present, there is no standard procedure to conduct concrete fatigue tests. Data on fatigue from two different test setups cannot be directly

compared. The use of normalized fatigue strength with static strength partially eliminates the influence of geometric variables, such as the geometry of the specimen, the composition of the material, curing conditions, and age of test specimen.

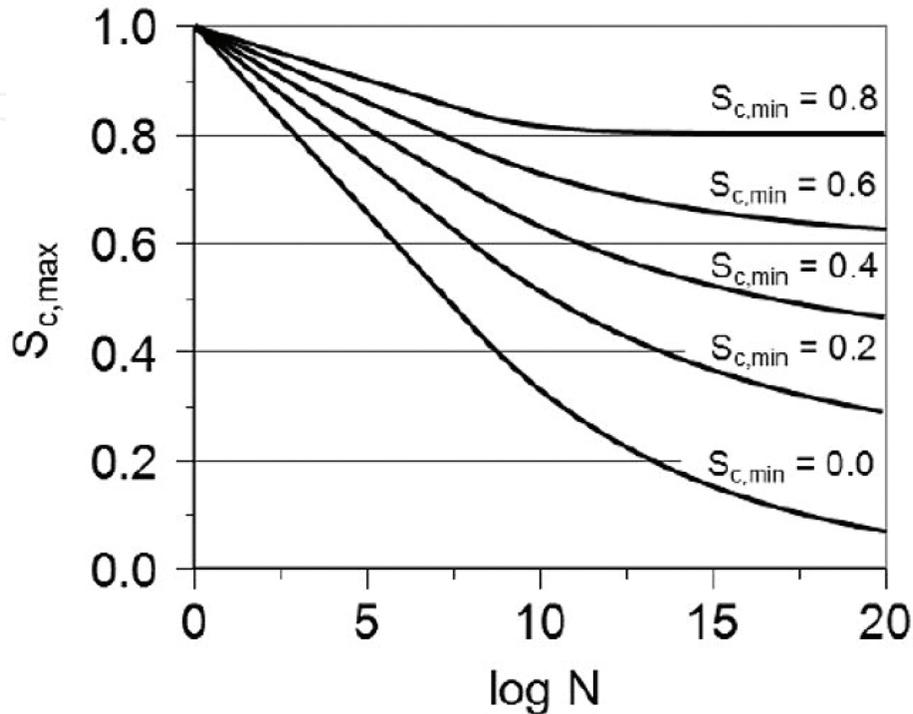


Figure 2. S-N for concrete [9].

3. Variable load cycles. Concept of damage

Structural concrete components are usually subjected to variable loads of random nature. To date, very few works have conducted in-depth examinations of the effect of random loading on the fatigue behavior of concrete. Most of the tests have been performed under low cyclic loads with average stress values and amplitude that are constant.

Traditionally, the Palmgren-Miner rule or hypothesis of the accumulation of linear damage is applied, in order to estimate the number of cycles that provokes the failure of the concrete specimen subjected to different series of cyclic loads, each one of them with different maximum and minimum stress levels.

This rule defines the damage provoked by cyclic loads, with constant values of both average stress and amplitude, as the quotient between the number of cycles that are applied and the number of cycles that it withstands. In addition, the principle of superimposition of damage is assumed, which implies that the damage provoked by one cyclic load is unrelated to the damage provoked by another. Therefore, the global damage applied to an element subjected to cyclic loading may be obtained from the following expression (1):

$$D = \sum_{i=1}^n D_i \sum_{i=1}^n \frac{n_i}{N_i} \quad (1)$$

where “ D ” is the global damage or accumulated damage. A value of 1 is taken as the design value, to determine a situation of maximum damage; n_i is the number of cycles at a certain level of loading; and N_i is the fatigue strength for a certain level of loading.

The theory of linear damage proposed by Miner is not directly applicable to concrete specimens subjected to variable loads of random nature. Numerous investigations call this assumption into question [12–18].

The effects of alternating periods of rest and loading on fatigue behavior are not sufficiently well studied. Laboratory tests have shown that rest periods and/or maintained loads between two periods of cyclic loading tend to increase the fatigue strength of the concrete [19]. However, if the maintained loads are over 75% of static compressive strength, they can provoke negative effects on fatigue life [20]. This contradictory effect of creep stress may be explained if we consider that low levels of continuous loading improve the compressive strength of the concrete, while high values of continuous loading provoke an increase in internal microcracking and can facilitate collapse.

4. Main parameters affecting fatigue strength

Fatigue life and its variation during the fatigue process are conditioned by various factors. The most important ones are shown below.

4.1. Type of load and its variation

The way in which the load is progressively applied to the structural element influences concrete fatigue. It means that the stress range, the eccentricity of the load, and its frequency influences concrete fatigue.

Each one of these variables is analyzed as follows.

4.1.1. Stress range

As explained before, fatigue life depends on maximum stress and minimum stress levels, as can be seen in **Figure 2**.

Maximum stress values imply a shorter fatigue life of the material.

In addition, an increase in the stress range R , defined as $\sigma_{min}/\sigma_{max}$ leads to a reduction in fatigue life.

4.1.2. Load eccentricity

Load eccentricity is a very important factor, because when a stress gradient is applied, collapse occurs when the most solicited fiber reaches, approximately, its fatigue life without a significant stress redistribution. There are only very few works in this field. The load is usually applied centered, without any eccentricity, during the fatigue tests under compression. The study carried out by Ople and Hulsbos [21] is worth mentioning.

4.1.3. Load frequency

The frequency of the load has an influence on fatigue life. At present, it is accepted that frequency values between 1 and 15 Hz hardly have any influence on fatigue life, provided that the maximum stress level is not over 75% of the compressive strength [22–26]. Noteworthy is the research developed by Zhang and Wu [27], which proposed, for the first time, an S-N curve as a function of the frequency of the cyclic load.

It is worth highlighting the studies conducted over recent years by Saucedo et al. [28] and Medeiros et al. [29]. Their works offer an in-depth analysis of the response of the concrete to low-frequency cyclic loads. Their results show that the fatigue life N in very low test frequencies (1/16 Hz) is, at least, of a lower order of magnitude than the fatigue life obtained under higher test frequencies (4 Hz).

4.2. Moisture content

It is well known that concrete is a hygroscopic material and its mechanical parameters are conditioned by the moisture content. The fatigue response is also influenced by the concrete moisture content.

The works developed by Waagaard and others [30] are worth mentioning. These researchers investigated the effect of dry and humid mixtures on the fatigue behavior of high-performance concretes with normal and lightweight aggregates. Some of the specimens were tested dry and others saturated moisture. Their principal result was that the fatigue life of the dry specimens was longer than the humid specimens under the same stress levels. This effect was more evident in concretes of normal density.

It is a very interesting conclusion, especially in case of fatigue characterization tests, given that, on some occasions, the differences in behavior between the different specimens may be due to differences in their humidity content.

4.3. Effect of fibers on the fatigue behavior of concrete

Fibers improve the fatigue life of the concrete, especially under tension and bending efforts, and, to a lesser extent, under compression efforts. Their use is very common in concrete pavements. Their use in structural concrete elements (beams and slabs among others) is still very limited.

The most commonly used are metallic and polypropylene fibers. They show good behavior under static loads and they are inexpensive. There are other types of fibers, although they are

far less widely used. Among these, carbon and glass fibers may be mentioned. Both fiber types show a good structural behavior, but their price is still very high. They are more commonly used as external reinforcements, within a polymeric matrix, instead of as an additive placed inside the concrete mix.

The following sections present an analysis of the effect of different fiber types on the fatigue response of the concrete.

4.3.1. *Steel fibers*

Steel fibers are the most widely used in concrete. They are usually used in reinforced and/or prestressed concrete elements, together with passive and/or active reinforcements, with the purpose of improving their behavior under certain conditions. Over recent years, a significant advance on the use of fibers as a substitute for passive reinforcement is occurring.

In the case of steel fibers, experimental studies [31, 32] show that the metallic fibers improve fatigue bending strength. Depending on the type of fiber employed and its percentage addition, a concrete with steel fibers with an acceptable design can maintain a residual fatigue strength of between 65% and 90% of its static strength after 2,000,000 cycles. The addition of fibers in appropriately reinforced concrete beams increases their fatigue life, and a reduction in fatigue-related cracks. In addition, fiber additions also reduce deformation in beams during the fatigue process.

Benefits of fibers in case of specimens subjected to compression efforts are less significant. As Lee and Barr [33] indicated, it cannot be said, in general terms, that the presence of fibers improves the fatigue life of the concretes. This seems to be due the effect of two opposite phenomena. On the one hand, fibers bind the microcracks that appear within the material due to fatigue loads. On the other hand, fibers produce an increase in the density of the initial microcracking, causing a decrease in the initial strength. The combination of these opposing factors may be the cause of the increased or the decreased fatigue life of the concrete.

As mentioned in this document, there are many variables that influence the fatigue life of a concrete and the presence of fibers will not always improve their behavior.

It is worth highlighting the works of Saucedo et al. [28], which demonstrate that, under low frequencies (of around 0.1 Hz), the fatigue life of fiber-reinforced concrete is as much as 10 times greater than then fatigue life of concrete that contains no fibers.

It is worth noting that fatigue-related deformation is greater in fiber-reinforced concrete. This is because fibers provide ductility to concrete specimen.

4.3.2. *Polypropylene fibers*

Polypropylene fibers are also widely employed in concrete, because they present good mechanical behavior and they are inexpensive. They moreover manage to improve the fire-resistant behavior of structural concrete components.

The influence of the content of polypropylene fibers on the fatigue life of concrete specimens under bending efforts has been studied [32]. Almost all the research conducted on fiber-reinforced concrete have studied fatigue under bending efforts.

It is worth mentioning the studies carried out by Ramakrishna and Lokvik [34]. They show how the incorporation of polypropylene fibers, even in small quantities, increase fatigue-related bending strength. Fatigue strength increased between 15% and 38% at 2,000,000 cycles at different percentage additions of fibers (between 0.1% and 1% by volume).

In the same way as steel fiber-reinforced concrete, polypropylene-reinforced concrete showed an increase in residual static bending strength, after having been subjected to fatigue loads. It may therefore be said that an increase in bending strength exists in polypropylene fiber-reinforced concrete, when subjected to fatigue cycles below the stress limit for fatigue-related failure.

There is a very limited amount of research focused on the influence of polypropylene fiber on the fatigue response of concrete specimens under compression efforts. The works carried out by Minguez [35] may be highlighted, among others.

4.3.3. Fiber quantity and orientation

According to fluid dynamics, the fibers are oriented along the concrete flow during concreting. In addition, fiber orientation is conditioned by the shape and the effect of the concrete formwork as well as the presence of internal obstacles such as passive and/or active reinforcements. These fibers tend to assume positions in parallel to the walls of the formwork when in their proximity. Moreover, the vibrating process also modifies the fiber orientation.

Fiber orientation influences fatigue insofar as the energy-related processes of damage are delayed or reduced by a binding effect of the fibers in the internal matrix of the concrete mix. It may therefore be expected that orientations in the direction parallel to the direction of cracking will generate disadvantageous effects on fatigue life as opposed to those orientations that bind the cracks provoked during the deterioration process of the material.

There are different methods to measure fiber orientation within the concrete matrix. In the case of metallic fibers, indirect methods permit the determination of fiber orientation by means of electromagnetic capabilities that detect the presence of metallic fibers through the use of magnetic fields or by using impedance-based techniques.

Direct methods permit the definition of fiber position, density, and orientation with greater precision. These methods include the use of computerized tomography technology that provides information on the fibers taken from scanned images [36].

5. Fatigue as a degenerative process

One of the differentiating characteristics of fatigue in concrete as opposed to fatigue in other (especially metallic) materials is that the energy transmitted by the cyclic load to the concrete

elements provokes internal structural damage that manifests itself in the birth and growth of internal microcracks, causing “diffuse damage” (**Figure 3**).

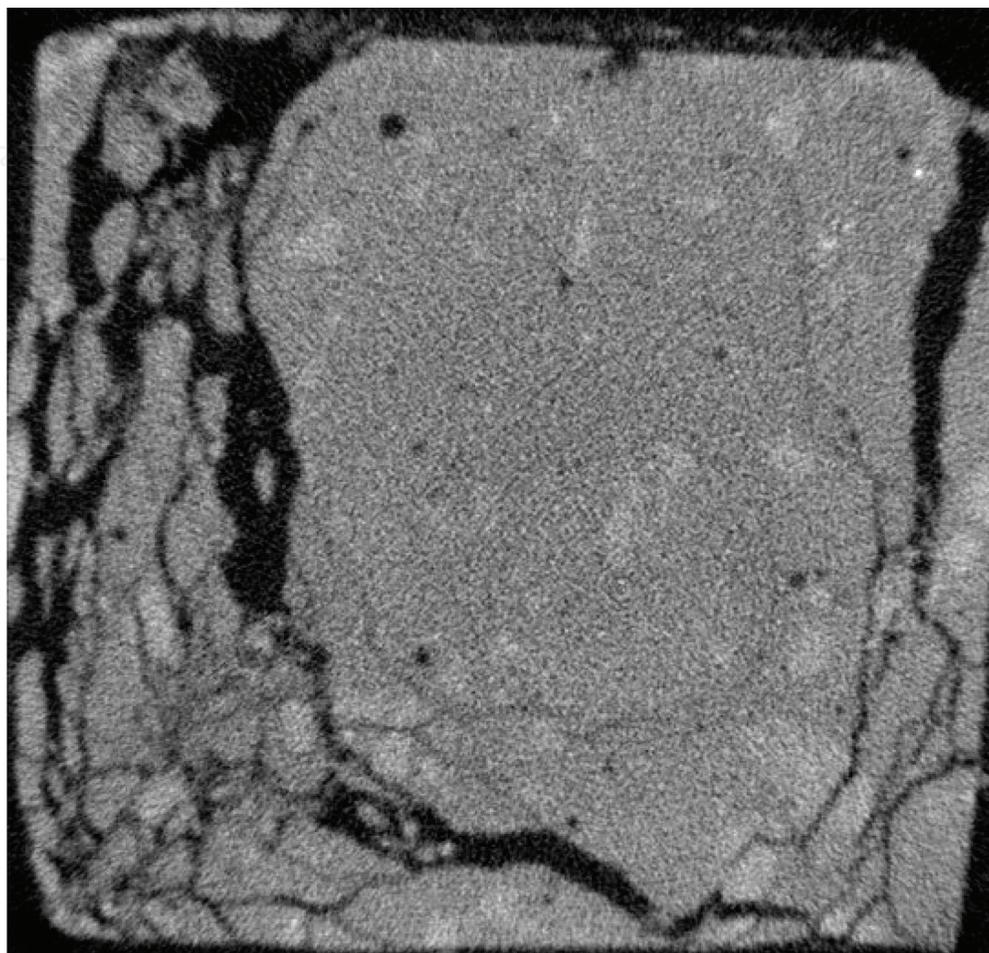


Figure 3. CT scan image of a concrete specimen with internal cracking. Courtesy of Research Group AUSINCO—University of Burgos (Spain).

The macroscopic result is a progressive variation of the mechanical parameters of the concrete, compression strength and Young’s modulus, as well as an appearance of residual strain of increasing value.

It is worth noting that the energy transmitted by cyclic loads, in metallic materials, is concentrated at the edge of the crack, causing it to expand. The material that is not close to the crack undergoes no modification whatsoever in its mechanical parameters.

5.1. Variation of deformation with the number of cycles

Concrete specimens subjected to fatigue testing show a progressive modification in the stress-strain diagram with the number of cycles, characterized by the birth and growth of residual deformation, and by a progressive reduction in the modulus of elasticity of the material (**Figure 4**).

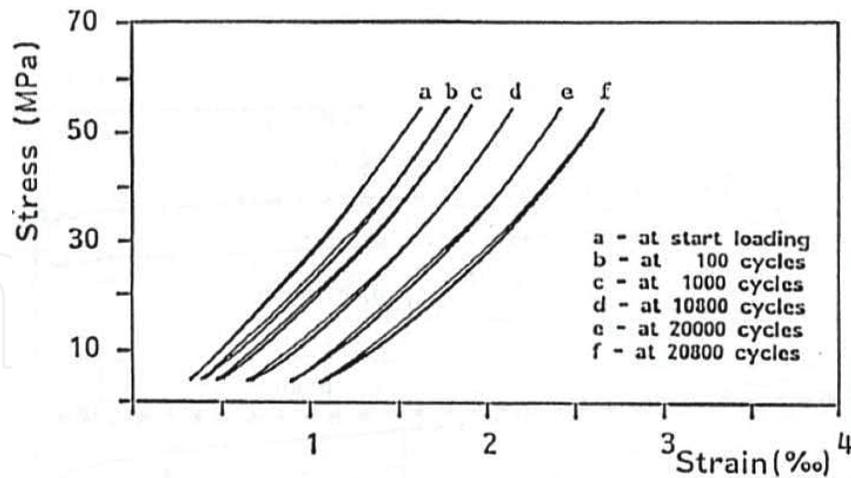


Figure 4. Variation of the stress-strain diagram with the number of cycles [6].

In a continuous fatigue-related degradation process, three phases of increasing damage were noted:

(1) A first phase with an increasing speed of damage. This phase corresponded to the formation of microcracks along the aggregate-paste interface and was characterized by a significant deterioration in the properties of the concrete. It lasts for approximately 10–15% of the fatigue life.

(2) A second phase with a speed of damage that was basically constant. This phase describes the stable propagation of the microcracks and was characterized by a constant speed of deformation and also a constant reduction of the modulus of elasticity. The second phase lasted for 80–90% of the fatigue life.

(3) A third phase with an increased speed of damage. The interconnections between the microcracks take place and finally the specimen collapse. In the third phase, the deterioration of the material is also very important.

This behavior is shown in the deformation-load cycle curves shown below (**Figure 5**).

These three phases were noted in all of the concrete specimens that were tested. However, the second phase is longer for higher strength concretes. The greater the strength of a concrete, the lower the ultimate fatigue-related deformation up until failure, for the same range of stress levels. This indicates that the internal damage is much greater for a high-strength concrete when fatigue-related failure occurs.

The slope of the straight line in the second phase is known as the secondary creep rate. This is a very interesting parameter that may be used as an estimator of fatigue life without any need to conduct failure tests. Numerous investigative works have demonstrated that there is a direct relation between the secondary creep rate and the fatigue life. The secondary creep rate depends on the loading frequency and the maximum strain level [23, 28, 29, 37].

It is worth highlighting the works of Zanuy et al. [38], which propose a theoretical model for the evolution of maximum deformation as a function of damage.

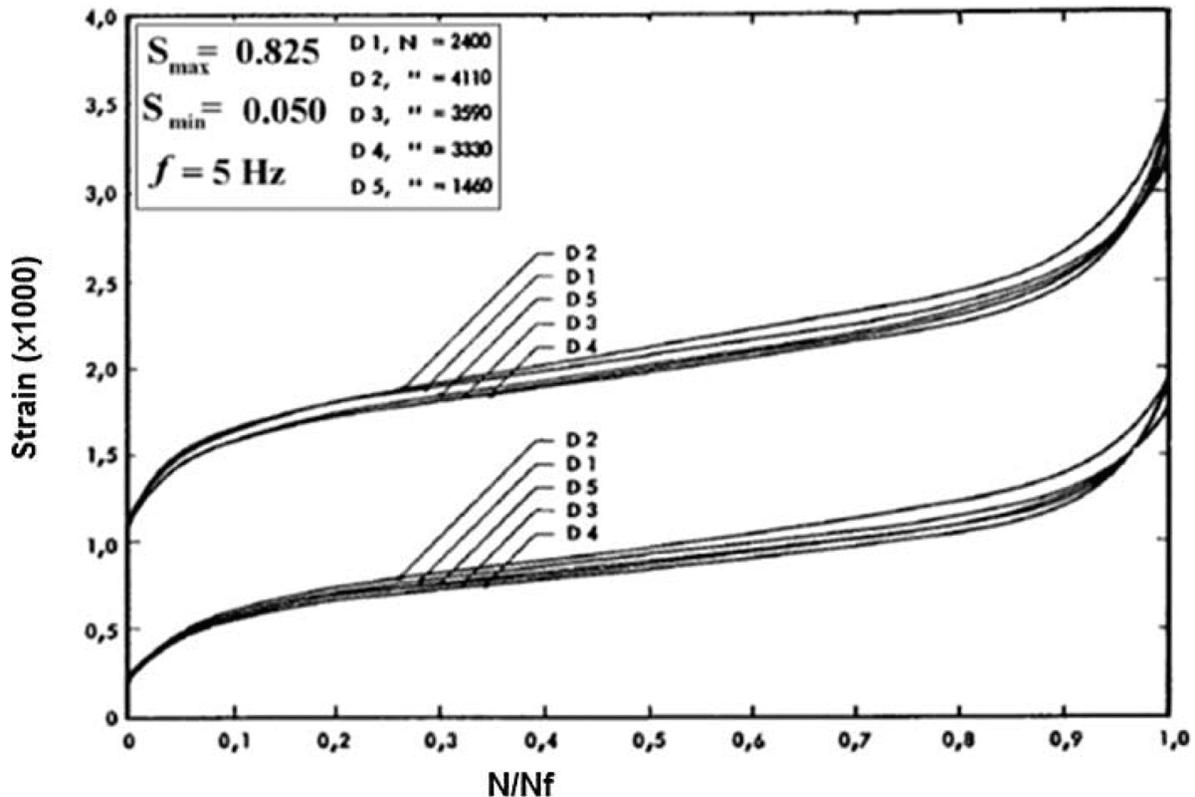


Figure 5. Variation of the maximum and minimum strains with the number of cycles [15].

5.2. Variation of the modulus of elasticity with the number of cycles

As has been described in earlier sections, fatigue provokes changes in the internal structure of the concrete that modifies its mechanical properties. The modulus of elasticity is among the affected properties.

The work developed by Holmer [15] is the most exhaustive for the analysis of the behavior of the modulus of elasticity and deformation with regard to its experimental results. Some of the results are shown in the following figure.

The shape of the curve resembled the shape of the deformation curve observing three different phases. As in the case of deformation, this curve presents three phases. In the first phase, a significant decrease occurs in stiffness, provoked by the birth of cracks. In the second phase, a linear reduction in the modulus of elasticity occurs, corresponding to a stage of progressive increase in cracks. In the third phase, an accelerated decrease in the modulus of elasticity takes place, corresponding to the phase in which the microcracks reach the critical lengths and the concrete specimen become unstable (Figure 6).

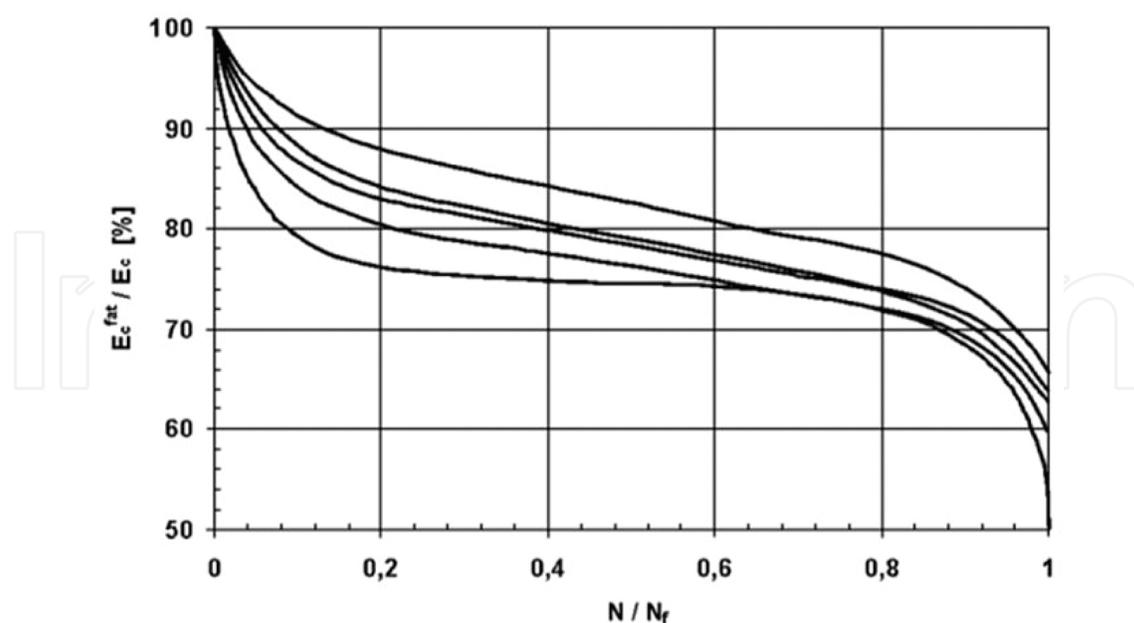


Figure 6. Variation of the modulus of elasticity with the number of cycles [15].

The following conclusions may be drawn from the above figure:

1. During the first phase, the reduction in the modulus of elasticity is greater at lower stress levels.
2. In contrast, in the second phase the contrary occurs, producing a curve close to the horizontal at low-stress levels.

In the same way as for the variation of fatigue-related deformation, Zanuy [38, 39] proposed some adjustment equations that attempted to model the behavior of the variation in the modulus of elasticity with fatigue damage.

It was observed that under the circumstance of stress ranges below 0.40, the maximum stress value had no influence on the model proposed by Zanuy [38, 39]. In contrast, for values over the stress range, the different maximum and minimum stress ranges yielded differentiated curves.

A reduction in the Young's modulus with cyclic loading is of great importance, given its implications for structural elements under cyclic loading, which produces a progressive loss of stiffness, bringing with it many structural consequences [38–41]:

- (1) Progressive increase in vertical deflection in bridges and viaducts. Not only under live loads, but also under dead loads.
- (2) Progressive reduction in the natural frequency.
- (3) Increased losses of prestressing/posttensioning.
- (4) Increased anchorage length in reinforcement bars.
- (5) Increased transference length in prestressed wires.

It is important to point out that the modulus of elasticity that is obtained corresponds to the dynamic modulus of elasticity measured during the cyclic loading of the specimen (usually named as dynamic modulus of elasticity). This information is slightly different from the static modulus of elasticity, given by the specific test in ASTM C469. Some interesting research has been conducted on the measurement of the variation in the static modulus of elasticity with the number of cycles [42].

5.3. Variation of the compression strength with the number of cycles

Residual fatigue strength may be defined as the static strength, after having subjected the specimen to different fatigue cycles. It is a very important parameter for the analysis of damage that existing structures may present, in order to plan maintenance and repair works.

There are very few works in relation to how compression strength varies with the number of cycles [35, 42]. It is a parameter that cannot be measured during cyclic loading (unlike the deformation and the modulus of elasticity). However, it appears logical to think that residual compressive strength might be reduced with the birth and growth of microcracks under cyclic loading.

Minguez [35] conducted studies to verify postfatigue parameters at low-stress ranges in concretes without fibers and in concretes reinforced with polypropylene fibers. The results of their works showed an increase of the residual compressive strength at the first levels of fatigue. They proposed that, during this early damage stage, a recompacting process of concrete occurs. On the other hand, microcracking leads to a progressive reduction of the compressive strength, but this effect has structural consequences later than the recompacting process. The structural consequence of both phenomena is an initial maturation of concrete, with a progressive increase of the residual compressive strength, and later a progressive reduction of it.

The process of concrete maturing due to fatigue has the following effects in the concrete microstructure:

- (1) Consolidation of the concrete at a microscopic level.
- (2) Greater stability due to reorientation of the atomic structure.
- (3) Reduction of localized stress in the paste-aggregate interface.
- (4) Uniform redistribution of localized shrinkage stresses in the concrete.

6. Bi- and tridirectional fatigues

The presence of cyclic stress in two and/or three directions substantially modifies the fatigue response. However, there is, in general, a scarcity of works that have been developed to date.

Relevant works on biaxial compression are scarce [43–48]. The study conducted by Nelson et al. [46] is noteworthy. It describes tests performed on cubic specimens under biaxial compres-

sion, with two different transverse compression values: 10 and 25% of the vertical compression. The levels of maximum load fluctuated between 0.50 and 0.90, and the minimum load level was, in all cases, 10% of the maximum load.

It was observed that, in all cases, the number of cycles that provoked collapse was greater in the case of greater transversal confinement. As a result of their work, they presented a diagram that correlated the number of cycles that provoked failure with the maximum stress in both directions (Figure 7):

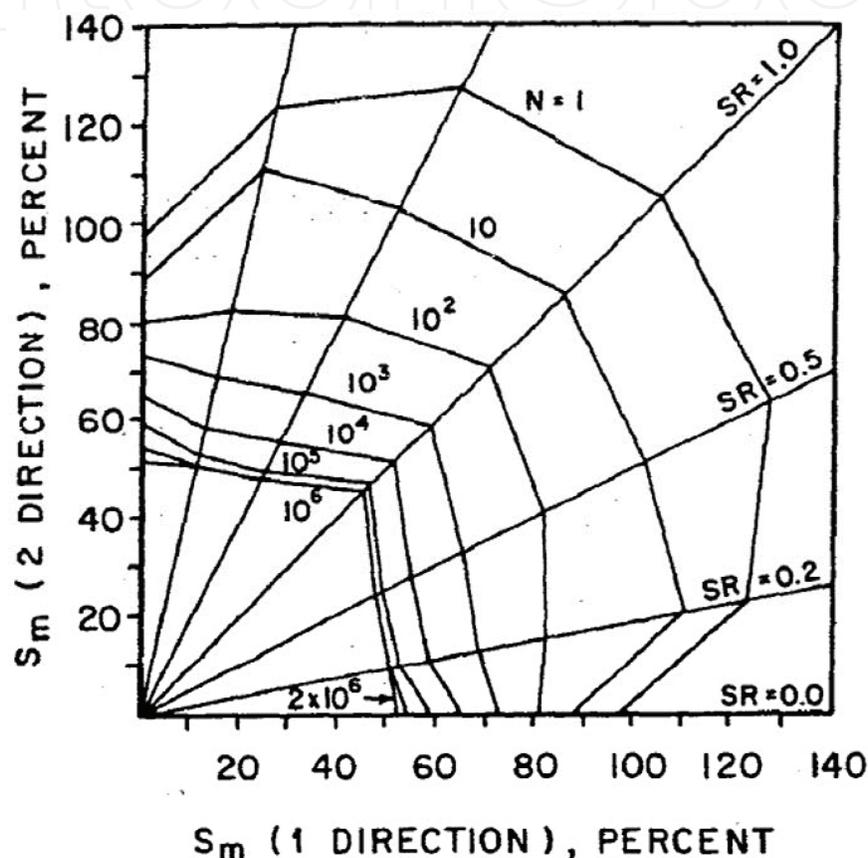


Figure 7. Fatigue envelope diagram [46].

In all cases, the results were not completely conclusive, because they were limited by their test campaign. It was also observed that the confinement improved material ductility that favors the reduction of the modulus of elasticity and the stress redistribution of forces, among other phenomena.

The work conducted by Su and Hsu [47] was also of great interest. In this case, stress with number of cycles of up to 10^7 cycles are performed for different biaxial ratios (Figure 8).

Finally, there are very few works related to biaxial friction fatigue [49–52]. It is a topic of much less interest in the case of concrete mixtures, holding greater interest in the case of fiber-reinforced concretes. Moreover, no conclusive results have been obtained to date.

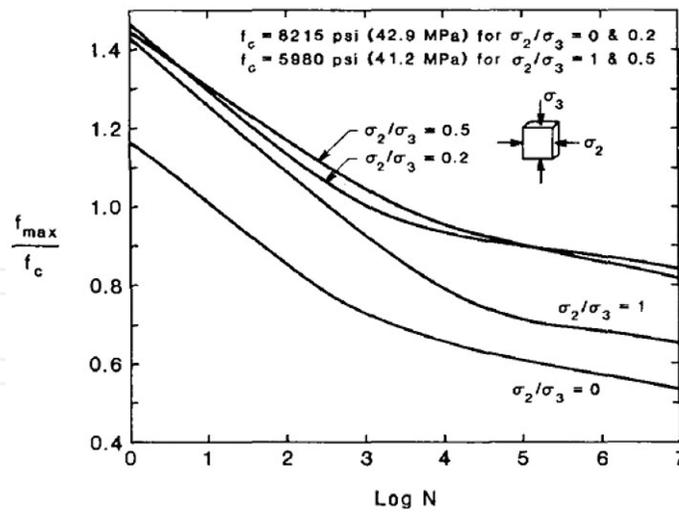


Figure 8. S-N curves for different biaxial compression ratios [47].

7. Deterministic and probabilistic models for the determination of fatigue-related failure

One of the characteristics of concrete, in relation to the number of cycles that it can withstand up until fatigue-related collapse, is its high variability.

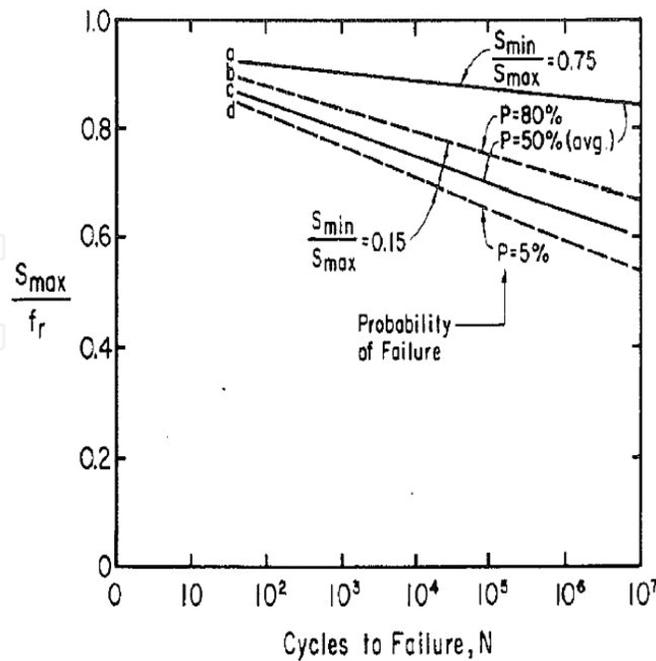


Figure 9. S-N-P curves [53].

Many research works have been developed in this field and they all conclude that the difference in the number of cycles that two “identical” specimens can withstand can be of two orders of magnitude. This observation greatly complicates the analysis of the results.

The analysis of the results in terms of probability is essential. So, it makes greater sense to develop S-N-P curves; it means, to develop S-N curves for different failure probabilities (P) (Figure 9).

On this point, two approaches may be found to present S-N curves: through the development of deterministic models and through the development of probabilistic models. The following describes each of the approach.

7.1. Deterministic models

Deterministic models, in essence, consist of showing explicit S-N curves for different failure probability values. In all cases, concrete compression strength is a deterministic value, characterized either by the average strength or by the characteristic strength of the concrete sample.

It is the traditional form of showing S-N curves and many researchers have developed expressions in this way [3, 6, 12, 15, 22, 25, 31, 33, 54–58].

The expressions specified in international standards fit this approach [9, 59].

7.2. Probabilistic models

The main problem of the deterministic models is that they consider the compression strength of concrete as a deterministic value, without taking into account the specific scatter of the concrete compression strength.

Over recent years, probabilistic failure models have been developed that take into account the statistical scatter of concrete strength in the estimation of the number of fatigue cycles [28, 60–63].

8. Conclusions

Fatigue is a degenerative process of concrete leading to collapse. The presence of cyclic loads provokes a progressive degradation that conducts the collapse of the structure. Cyclic loads provoke the birth and growth of microcracks inside the concrete and, finally, the structure fails.

The classic way of approaching fatigue in concrete corresponds, in essence, to an adaptation of metal fatigue. The basic parameter is the fatigue life “N”, defined as the number of cycles that provokes the collapse of the element. Unlike metals, the fatigue life of concrete elements depends on its maximum and the minimum stress levels. Alternatively, fatigue strength is defined as the maximum tensile stress that has to be applied to cause the failure of the material, following a certain number of cycles.

Many parameters have relevant influence on the response of concrete under cyclic loads. The most important are: stress range, load eccentricity, load frequency, moisture content, etc. Also the presence of fibers within the concrete improves its behavior under cyclic loads. Related to fibers, the most important parameters are quantity and orientation.

Unlike with metals, the energy of the cyclic loads applied to the material is converted into “diffuse damage.” This type of damage has macroscopic consequences, among which a progressive variation of the basic mechanical parameters of the material may be highlighted (compressive strength and elasticity modulus, among others). Its consequences are important and to date are not well studied.

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References

- [1] De Joly. Strength and elasticity of Portland Cement (La résistance et l'élasticité des ciments Portland) (in French). *Annales des Ponts et Chaussée, Memoires*. 1898;16(7): 216–226.
- [2] Considere, M. Influence of rebar on the properties of mortars and concretes (Influence des armatures métalliques sur les propriétés des mortiers et bétons) (in French). *Compte Rendu de L'Academic des Sciences*. 1899;127:992–995.
- [3] Hsu, T.C.C. Fatigue of plain concrete. *ACI Journal*. 1981;78:292–305.
- [4] Richard, F.E., Brandzaeg, A., Brown, R.L. The failure of plain and spirally reinforced concrete in compression. Bulletin No 190. University of Illinois. Engineering Experimental Station. Urbana. III. 1929.
- [5] Jones, R. A method of studying the formation of cracks in material subjected to stress. *British Journal of Applied Physics*. 1952;3(7):229–232.
- [6] Petkovic, G., Lenschow, R., Stemland, H., Rosseland, S. Fatigue of high-strength concrete. *ACI Special Publication*. 1990;121:505–526.
- [7] Zanuy, C., Albajar, L., De la Fuente, P. Concrete fatigue process and its structural influence (El proceso de fatiga del hormigón y su influencia estructural) (in Spanish). *Materiales de Construcción*. 2011;61(303):385–399.

- [8] Bazant, Z.P. Concrete fracture models: testing and practice. *Engineering Fracture Mechanics*. 2002;69:165–205.
- [9] International Federaci3n for Structural Concrete. FIB Bulletin, 65, editors. MODEL CODE 2010. Lausanne, Switzerland: Ernst & Sohn; 2010.
- [10] Cornelissen, H.A.W. Fatigue failure of concrete in tension. *HERON*. 1984;29(4):68.
- [11] Paskova, T., Meyer, C. Optimum number of specimens for low-cycle fatigue test of concrete. *Journal of Structural Engineering*. 1994;120:2242–2247.
- [12] Oh, B.H. Fatigue-life distributions of concrete for various stress levels. *ACI Materials Journal*. 1991;88(2):122–128.
- [13] Cornelissen, H.A.W., Reinhardt, H.W. Uniaxial tensile fatigue failure of concrete under constant amplitude and programme loading. *Magazine of Concrete Research*. 1984;136(129):216–226.
- [14] Shah, S.P. Predictions of cumulative damage for concrete and reinforced concrete. *Materiaux et Constructions*. 1984;17(47):65–68.
- [15] Holmer, J.O. Fatigue of concrete by constant and variable amplitude loading. *ACI Special Publication. Fatigue of Concrete Structures*. 1982;75:71–110.
- [16] Siemes, A.J.M. Miner's rule with respect to plain concrete. *ACI Special Publication. Fatigue of Concrete Structures*. 1982;75:343–372.
- [17] Leeuwen, J.V., Siemes, A.J.M. Miner's rule with respect to plain concrete. *HERON*. 1979;24(1):1–34.
- [18] Tepfers, R., Friden, C., Georgsson, L. A study of the applicability to the fatigue of concrete of Palgrem-Miner partial damage hypothesis. *Magazine of Concrete Research*. 1977;29(100):123–130.
- [19] Hilsdorf, H.K., Kesler, C.E. Fatigue strength of concrete under varying flexural stresses. *ACI Journal Proceedings*. 1966;63(10):1059–1076.
- [20] Shah, S.P., Chandra, S. Fracture of concrete subjected to cyclic loading. *ACI Journal Proceedings*. 1970;67(10):816–824.
- [21] Ople, F.S., Hulsbos, C.L. Probable fatigue life of plain concrete with stress gradient. *ACI Proceedings*. 1966;63(1):59–82.
- [22] Zhang, B., Philips, D.V., Wu, K. Effect of loading frequency and stress reversal of fatigue life of plain concrete. *Magazine of Concrete Research*. 1996;48(117):361–375.
- [23] Sparks, P.R., Menzies, J.B. Effect of rate of loading upon the static and fatigue strengths of plain concrete in compression. *Magazine of Concrete Research*. 1973;25:73–80.

- [24] Awad, M.E., Hilsdorf, H.K. Strength and deformation characteristics of plain concrete subjected to high repeated and sustained loads. *Civil Engineering Studies, Structural Research Series*. No 372. 1971; pp.266.
- [25] Aas-Jakobsen, K. Fatigue of concrete beams and columns. University of Trondheim. Norwegian Institute of Technology. Division of Concrete Structures. 1970;70(1):pp.148.
- [26] Murdock, J.W. A critical review of research on fatigue of plain concrete. Engineering Experiment Station. University of Illinois Urbana. Bulletin N0 475. 1965.
- [27] Zhang, B., Wu, K. Residual fatigue strength and stiffness of ordinary concrete under bending. *Cement and Concrete Research*. 1997;27(1):115–126.
- [28] Saucedo, L., Yu, R.C., Medeiros, A., Zhang, X.X., Ruiz, G. A probabilistic fatigue model based on the initial distribution to consider frequency effect in plain and reinforced concrete. *International Journal of Fatigue*. 2013;48:308–318.
- [29] Medeiros, A., Zhang, X.X., Ruiz, G., Yu, R.C., Velasco, M. Effect of the loading frequency on the compressive fatigue behavior of plain and fiber reinforced concrete. *International Journal of Fatigue*. 2015;70:342–350.
- [30] Waagaard, K., Keep, B., Stemland, H. Fatigue of high strength lightweight aggregate concrete. *Proceedings of the Utilization of high strength concrete, Stavanger (Norway)*. 1987:291–306.
- [31] Cachim, P.B., Figueiras, J.A., Pereira, P.A.A. Fatigue behavior of fiber-reinforced concrete in compression. *Cement and Concrete Composites*. 2002;24(2):211–217.
- [32] ACI Committee 544, editor. State-of-the-art report on fiber reinforced concrete. American Concrete Institute; 2002.
- [33] Lee, M.K., Barr, B.I.G. An overview of the fatigue behavior of plain and fibre reinforced concrete. *Cement and Concrete Composites*. 2004;26:299–305.
- [34] Ramakrishnan, V., Lokvik, B.J. Fatigue strength and endurance limit of plain and fibre reinforced concretes. A critical review. *Proceedings of the International Symposium on Fatigue and Fracture in Steel and Concrete Structures, Madras (India)*. 1991:381–407.
- [35] Minguez, J. Analysis of the post-cracking mechanical capacity of high performance concrete subjected to axial cyclic loads (Análisis de la capacidad mecánica postfatiga en hormigones de altas prestaciones sometidos a cargas cíclicas axiales) (in Spanish) [thesis]. Burgos (Spain): University of Burgos; 2012. 302 p.
- [36] Vicente, M.A., González, D.C., Mínguez, J. Determination of dominant fibre orientations in fibre-reinforced high-strength concrete elements based on computed tomography scans. *Nondestructive Testing and Evaluation*. 2014;29(2):164–182.
- [37] Oneschkow, N. Influence of loading frequency on the fatigue behaviour of high-strength concrete. In: FIB, editor. *Proceedings of the 9th FIB International PhD Sym-*

- posium in Civil Engineering. July 22nd to 25th; Karlsruhe (Germany). 2012. pp. 235–240.
- [38] Zanuy, C., Albajar, L., De la Fuente, P. Sectional analysis of concrete structures under fatigue loading. *ACI Structural Journal*. 2009;106(5):667–677.
- [39] Zanuy, C. Sectional analysis of reinforced concrete elements subjected to fatigue loads, including sections between cracks (Análisis seccional de elementos de hormigón armado sometidos a fatiga incluyendo secciones entre fisuras) (in Spanish) [thesis]. Madrid (Spain): Polytechnic University of Madrid. 2008. 275 p.
- [40] Vicente, M.A., González, D.C., Martínez, J.A. Mechanical response of partially prestressed precast concrete I-beams after high-range cyclic loading. *ASCE Practice Periodical on Structural Design and Construction*. 2014;20(1):1-8. DOI: 10.1061/(ASCE)SC.1943-5576.0000225
- [41] Bernardo, H., Vicente, M.A., González, D.C., Martínez, J.F. Cyclic bond testing of steel bars in high-performance underwater concrete. *Structural Engineering International*. 2014;24(1):37–44.
- [42] Vicente, M.A., González, D.C., Mínguez, J., Martínez, J.A. Residual modulus of elasticity and maximum compressive strain in HSC and FRHSC after high-stress-level cyclic loading. *Structural Concrete*. 2014b;15(2):210–218.
- [43] Meng, X.H., Wang, W.W., Zhou, J.J., Song, Y.P. Experimental investigation on residual strength of plain concrete under fatigue biaxial compression with constant confined stress. *Advances Materials Research*. 2011;261–263:581–585.
- [44] Wang, H.L., Song, Y.P. Fatigue capacity of plain concrete under fatigue loading with constant confined stress. *Materials and Structures*. 2011;44(1):253–262.
- [45] Zhu, J.S., Song, Y.P., Cao, W. Fatigue behaviour of plain concrete under biaxial compression: Experiments and theoretical model. *China Ocean Engineering*. 2003;17(4):617–630.
- [46] Nelson, E.L., Carrasquillo, R.L., Fowler, D.W. Behaviour and failure of high strength concrete subjected to biaxial-cyclic compression loading. *ACI Materials Journal*. 1988;85(3):248–253.
- [47] Su, E.C.M., Hsu, T.T.C. Biaxial compression fatigue and discontinuity of concrete. *ACI Materials Journal*. 1988;3:178–188.
- [48] Buyukozturk, O., Tseng, T.M. Concrete in biaxial cyclic compression. *Journal of Structural Engineering*. 1984;110(3):461–476.
- [49] Kim, J., Yi, C., Lee, S.J., Zi, G. Flexural fatigue behaviour of concrete under uniaxial and biaxial stress. *Magazine of Concrete Research*. 2013;65(12):757–764.
- [50] Subramaniam, K.V., Shah, S.P. Biaxial tension fatigue response of concrete. *Cement and Concrete Composites*. 2003;25(6):617–623.

- [51] Subramaniam, K.V., Popovics, J.S., Shah, S.P. Fatigue fractures of concrete subjected to biaxial stresses in the tensile C-T region. *Journal of Engineering Mechanics-ASCE*. 2002;128(6):668–676.
- [52] Subramaniam, K.V., Popovics, J.S., Shah, S.P. Fatigue response of concrete subjected to biaxial stresses in the compression-tension region. *ACI Materials Journal*. 1999;96(6): 663–669.
- [53] ACI 215R-74, editor. Considerations for design of concrete structures subjected to fatigue loading. American Concrete Institute. 1974. 24 p.
- [54] Paskova, T., Meyer, C. Low-cycle fatigue of plain and fiber-reinforced concrete. *ACI Materials Journal*. 1997;94:273–285.
- [55] Kim, J.K., Kim, Y.Y. Experimental study of the fatigue behaviour of high strength concrete. *Cement and Concrete Research*. 1996;26(10):1513–1523.
- [56] Grzybowski, M., Meyer, C. Damage accumulation in concrete with and without fiber reinforcement. *ACI Materials Journal*. 1993;90:594–604.
- [57] Furtak, K. A method for calculating the concrete strength under cyclic loads (Ein Verfahren zur Berchnung der Betonfestigkeit unter schwellender Belastungen (in German)). *Cement and Concrete Research*. 1984;14:855–865.
- [58] Tepfers, R., Kutti, T. Fatigue strength of plain, ordinary and lightweight concrete. *ACI Journal*. 1979;76(5):635–652.
- [59] FIB-Fédération International du Béton. Model Code 2010. Final Draft. Volume 1. International Federation for Structural Concrete (fib) Bulletin 65; 2012.
- [60] Przybilla, C., Fernández-Cantelli, A., Castillo, E. Deriving the primary cumulative distributive function of fracture stress for brittle materials from 3- and 4-point bending test. *Journal of the European Ceramic Society*. 2011;31(4):451–460.
- [61] Castillo, E., Fernández-Cantelli, A., Koller, R., Ruiz-Ripoll, M.L., García, A. A statistical fatigue model covering the tension and compression Wöhler fields. *Probabilistic Engineering Mechanics*. 2009;24(2):199–209.
- [62] Castillo, E., Fernández-Cantelli, A., Ruiz-Ripoll, M.L. A general model for fatigue damage due to any stress history. *International Journal of Fatigue*. 2008;30:150–164.
- [63] Zhao, D.F., Chang, Q.Y., Yang, J.H., Song, Y.P. A new model for fatigue life distribution of concrete. *Key Engineering Materials*. 2007;348–349:201–204.

