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A Review on Fatigue Performance of Concrete Structures Part I: Loading Parameters, Current Prediction Models and Design Approaches

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ABSTRACT

This review paper highlights the most fundamental state of knowledge regarding the fatigue of concrete that is available through the literature over the last decades and reveals the areas that are needed for further investigation. The loading factors influencing the fatigue performance and the fatigue life estimation of concrete structures are taken into consideration. This review explores the impact of eight loading parameters on the fatigue life of concrete structures, and we aimed to be succinct in our investigation. Besides, we present a review on the deterministic and probabilistic approaches for fatigue life prediction. For example, in more recent studies, the utilization of machine learning techniques has been shown to outperform the traditional methods. The review gives adequate insight into the approach of some of the main current design codes for fatigue life prediction of concrete.

Key words: fatigue of concrete, design approach, prediction models, loading parameters, failure mechanisms

1 INTRODUCTION

A lot of structures are often subjected to repetitive cyclic loads such as sea waves, wind, machine vibration, and car traffic. The consequence of exposure to cyclic loading is a steady stiffness degradation of the structure, which may eventually lead to fatigue failure. It has been demonstrated that the repetitive application of loads can lead to the deterioration of various structures [1-5], primarily caused by the formation and propagation of microcracks within the cement matrix.

As the methods of analysis for concrete structures become more exact and require higher sustainability, the demand for more fundamental information on the behavior of concrete under cyclic loads has become more pressing. Besides, the continuous development of concrete material and the desire to optimize concrete structures emphasize the need for more accurate design methods. The increased optimization for slender structures that are exposed to different environmental conditions under a variety of loading sequences, such as offshore wind turbines that are required to endure a significant number of cyclic loads throughout their lifespans, highlights the issue of fatigue in concrete [6, 7]. The fatigue in concrete has been studied intensively during the last decades, yet the proper design methods remain scarce. This is partly due to the complexity of fatigue behavior in concrete and the lack of unified testing methods to allow proper comparison.

The fatigue phenomenon has been referred to long before it was scientifically documented. Albert [8], as one of the first scientific investigators in 1837, published a paper on conveyor chains that failed at low below the characteristic strength. Perhaps, the most important fatigue issue that resulted in a breakthrough of this phenomenon happened in 1870, when the fatigue of railway cart axles was concerned. The contributor to this investigation was Wöhler [9] who later presented the Wöhler laws. His work is known as Wöhler-curves (also known as S-N curves), a method to describe the fatigue capacity of a subject in different load levels, in which S or S_{max} stands for maximum stress level (maximum compressive stress divided by the reference stress at failure) and N is the number of cycles. Positive value of S represents compressive loading, while negative value indicates tensile loading. Figure 7 illustrates a representative S-N curve.

Unlike the isotropic material for which the fatigue capacity mostly depends on the load amplitude and the number of load cycles, the fatigue capacity of concrete structures depends on a variety of factors due to the complex non homogeneity of concrete. This review aims to highlight the available knowledge on fatigue behavior of concrete and summarize the effect of various factors on fatigue capacity. Therefore, to ease the process of following and linking different factors regarding the fatigue of concrete, the review is divided into two papers. In this paper, the focus is on loading parameters, fatigue life prediction, and design approach, whereas the companion paper aims to explore fatigue behavior on the material level [10].

2 LOADING PARAMETERS

2.1 Loading rate and frequency

Frequency of load is one of the parameters affecting fatigue performance. Stochastic frequency of loads in the environment is the main obstacle for researchers to thoroughly investigate this phenomenon's real effect on fatigue life. The effect of frequency on fatigue performance has been investigated intensively, discovering different effects. Arthur et al. [11] performed an experimental approach to simulate the effect of the corrosive marine environment on fatigue life of concrete beams subjected to different load frequencies from 0.17 to 5 Hz and concluded no noticeable effect on fatigue life. This result corresponds with the findings obtained by other studies [12-14]. Murdock [12] did not find noticeable changes in fatigue life of concrete subjected to cyclic load frequencies in the range of 1.16 - 15 Hz at a given stress level of S_{max} < 0.75. On the contrary, at level of S_{max} > 0.75, Awad and Hilsdorf [15] found significant changes in fatigue life for different load rates, they concluded that the lower load rate results in lower fatigue strength.

The conclusion is in accordance with other results obtained by other studies [16-20]. Isojeh et al. [20] showed the influence of frequency on the number of cycles in Figure 1. The observation indicates that at a constant maximum stress level (S_{max}) and a stress range ratio (R, which is the ratio of the minimum stress level to the maximum stress level, and R equals zero when the compressive loading is completely unloaded in each cycle), an increase in frequency led to a greater number of cycles. This could be explained by considering an increase in stress and strain rates with increasing loading frequency, which generates more uniform redistribution of internal stresses and consequently, strength growth [21]. Although the effect of frequency has been a primary interest in fatigue analysis, static/cyclic loading rate is a key attribute of frequency effect, which also is a specifier in strength achievement. Most studies have focused on the stress level and load frequencies separately; that together make up the parameter of loading rate, which have resulted in a wide range of loading rates making it rather troublesome to compare the effects on fatigue strength. In this regard, Sparks [22] tested the effect of loading rate on fatigue strength. He concluded that an increase in loading rate would result in higher fatigue strength.

Taken together, the fatigue capacity is affected by both the frequency and the loading rate, and it is important to take both into account, especially when the reference strength is set to a fixed loading rate.

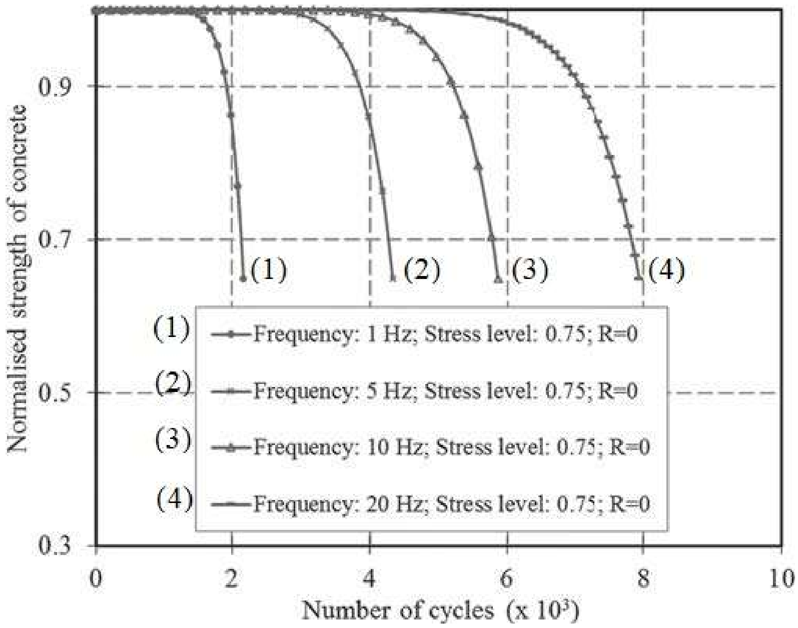

Figure 1 - Effect of frequency on the fatigue life at a constant maximum stress level and stress range ratio (R) [20].

2.2 Loading waveform

The parameter of the loading waveform is closely related to the frequency and loading rate, meaning that for each given frequency, different waveforms yield different ranges of loading rate. Tepfers [23] studied the effect of three different waveforms (triangular, sinusoidal, rectangular) on the fatigue life of concrete prisms subjected to compression. As seen in Figure 2, it was observed that the rectangular waveform caused more deformation for a certain number of loading cycles and induced failure after fewer loading cycles than the other waveforms. This is a logical observation as the specimens subjected to rectangular waveform loading experience higher stresses for a longer duration compared to other waveforms. On the contrary, the triangular waveform yielded the highest total number of cycles to failure as well as the largest final strain for a given cycle ratio. These results are in agreement with Oneschkow [24] that performed a comparative study between sinusoidal and triangular waveforms. It is undeniable that in a real situation, structures can undergo under nonharmonic loading cycles where the understanding of the effect of loading waveforms based on the studies mentioned above can be questioned.

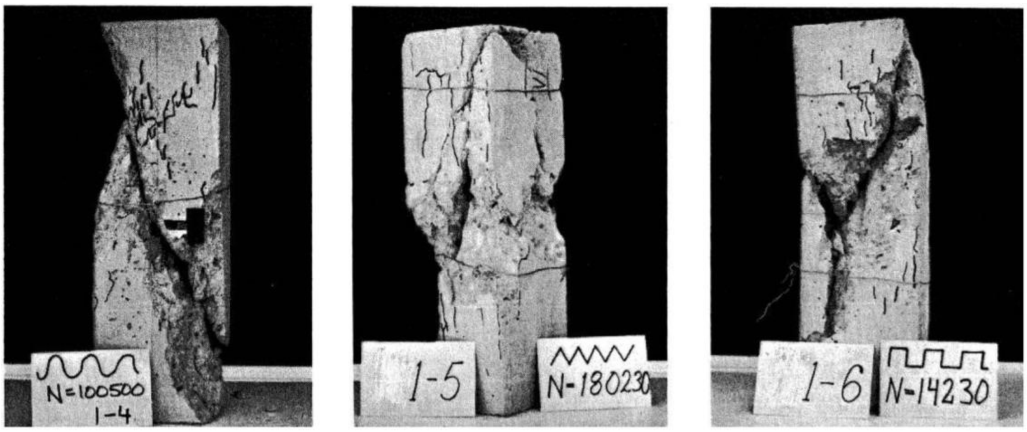

Figure 2 - Fatigue test subjected to different loading waveforms [23]

2.3 Multiple stage loading

In most of the studies only single stress range tests have been considered, thus, the full influence of stress range could not be unveiled by merely studying them in isolation. The effect of variable stress ranges was investigated in one of the early studies by Hilsdorf [2] on the flexural strength of concrete beams. Hilsdorf considered the effect, both in its simplest form with only two stress ranges, and a more complex multiple loading series, which are shown in Figure 3. n_1 and n_2 are the half of the number of cycles to failure. S_{min1} and S_{min2} are the minimum stress levels in a cyclic loading. In a cyclic loading, the highest and the lowest value of loading correspond to maximum stress level (S_{max}) and minimum stress level (S_{min}), respectively. Stress range or amplitude is the difference between S_{max} and S_{min}.

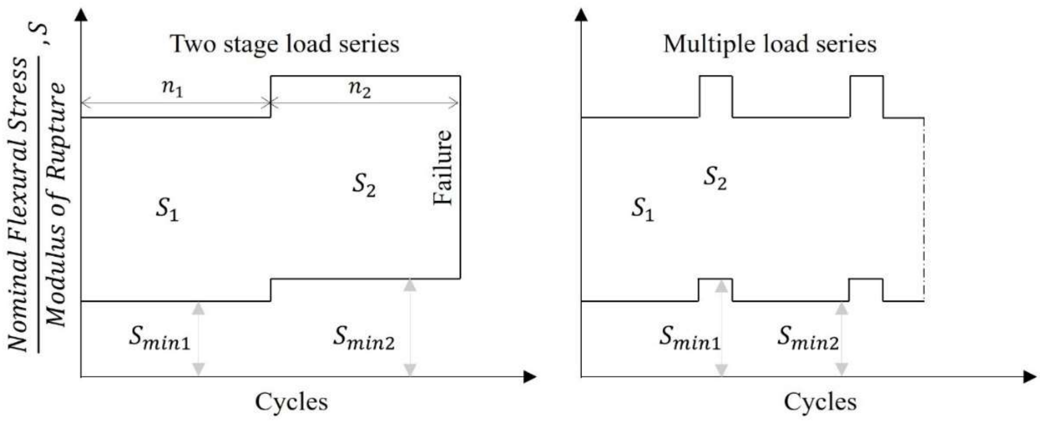

Figure 3 - Load series by Hilsdorf [2]

As for the simplest loading form, their results showed that the fatigue life is largely dependent on the order of the stress ranges, meaning that an increase in stress level on the subsequent stress range yielded a decrease in fatigue life. On the other hand, a decrease in stress level with the same stress range pattern yielded a longer fatigue life. They believed that this behavior is partly due to the changes of the relative stress level of the specimens with time, meaning that several sustaining cycles allow the actual concrete strength to increase due to the inducing stresses of opposite sign compared to those from shrinkage and relieving the residual stresses that naturally is present in the specimens due to the shrinkage. The extent of this mitigation was assumed to be dependent on the number of cycles and stress level; a higher loading can cause a higher strength increase as well as higher probability of severe damage per cycle compared to a lower loading. Thus, the benefit of strength increase has to be compared with the disadvantage of more severe damage.

Hordijk [25] found the same sequence effect by applying pure tensile loading to plain concrete. On the contrary, Oh [26] investigated plain concrete beams in a four-point bending test with two and three stage loading, either increasing S_{max} with each stage or decreasing and found that an increase in S_{max} yielded longer fatigue life, and decrease in S_{max} reduced the fatigue life. Although he did not explain the reason behind his finding, he proposed a nonlinear cumulative damage theory to model the effects of the magnitude and sequence of variable fatigue loading. This indicates that the validity of the Palmgren-Miner (P-M) rule, which relies on a linear cumulative damage hypothesis (see Section 3.2), could not be supported. Holmen [17] made a similar two stage loading tests as Hilsdorf [2], but on cylindrical specimens loaded in pure compression to assess the validity of P-M rule. Holmen concluded that the P-M rule is conservative if the stress level is increased, and unsafe when the stress level is decreased. Holmen's findings contradict the results found by Hilsdord. Although Holmen tested only 10 specimens in the two-stage loading configuration, his results are in agreement with Jinawath [27], Tepfers et al. [28], and Hoff [29] who investigated the effect of lightweight aggregate (LWA) concrete in compression. They [17, 27, 29] made a similar conclusion; going from a high stress level load to a lower stress level reduces the fatigue life, making the P-M rule unreliable.

A more recent study of multiple stage loading in compression was conducted by Baktheer and Chudoba [30]. Their study consisted of both theoretical and experimental analysis to explain the phenomenon of sequence effects. Their two-stage loading program revealed the similar sequence effect as found earlier by Holmen [17], namely that the P-M rule overestimates fatigue life when high stress is followed by low stress, and the opposite loading arrangement causes underestimation. The aim of their investigation was to provide a deeper understanding of how damage accumulates inside the specimen. They considered that there are two primary energy dissipative mechanisms: stiffness degradation and plastic strain. Although the plastic strain evolution might be seen as an indication of damage, they regarded the damage as a function of stiffness degradation. They use Equation 1 to track the damage (ω), where E is the stiffness at each point on the unloading branch of the stress-strain curve and E_0 is the initial stiffness.

$$\omega = 1 - \frac{E}{E_0} \tag{1}$$

In one of the loading scenarios, they applied a constant deformation repeatedly up until the stress decreases. As can be seen in Figure 4 the test showed a distinction in the behavior of damage development relative to strain development before and after maximum stress (pre- and post-peak). The illustration also reveals the fundamental characteristics of fatigue behavior in concrete, capturing the occurrence of inelastic processes that contribute to energy dissipation during the loading history, leading to phenomena like stiffness degradation and the formation of irreversible strains. Plastic sliding along the aggregate interface is thought to cause these plastic deformations (ε^p).

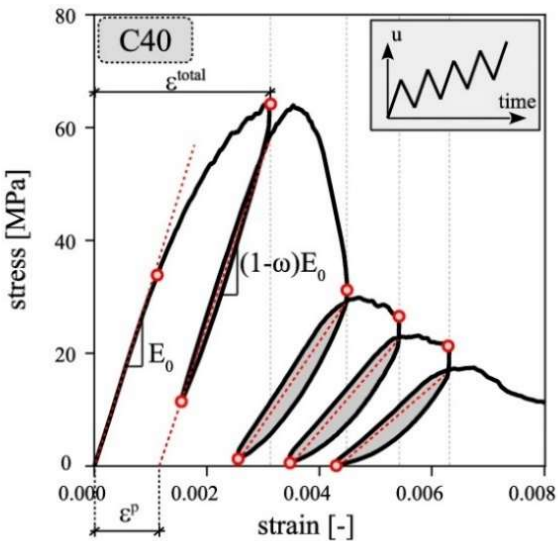

Figure 4 - The effect of cyclic deformation loading upon stress-strain relationship [30]

When additional stages or random loading are added, the complexity of varying loads increases. Hümme et al. [31] conducted three-stage compressive tests on normal strength concrete using decreasing (S_{max} = 0.8, 0.7 and 0.6) or increasing stress level (S_{max} = 0.6, 0.7 and 0.8). Their tests contradicted the proposed model from Baktheer and Chudoba [30] since the decreasing stress level setup resulted in an increased fatigue life, which is opposite to the reversed effect found in two-stage compressive loading by other studies [17, 20, 27-29, 32]. This is surprising as it goes against the sequence effect explanation provided by Baktheer and Chudoba. Unfortunately, Hümme et al. did not provide any explanation for their results or comments on the apparent discrepancy with previous studies. In fact, they did not perform two-stage loading test, making it challenging to determine if the behavior changes with three-stage loading compared to two-stage or if it is caused by another influencing factor.

As more stages or random loading are added, the issue of multiple stage loading becomes more complex. Baktheer and Chudoba's explanation of the sequence effect cannot account for certain effects and has limitations. Their model may not be valid for larger concrete structures that have a significant amount of macroscopic redistribution. Due to this, the behavior of an actual structure is expected to be different from that of small cylindrical specimens tested in laboratories. If redistribution also occurs in specimens during multiple stage load testing, it could explain some of the unpredictable results.

2.4 Stress level

Unlike steel, concrete is more influenced by maximum stress than stress range [33]. In spite of the large scatter in the result of fatigue testing, several researchers have found the logarithmic number of cycles to failure $\log(N_f)$ to be approximately normally distributed at each stress level [17, 27]. Several empirical formulas have generated a linear relation between maximum stress level and the logarithmic number of cycles to predict the fatigue life of plain concrete [18, 34, 35]. Holmen [17] plotted the cumulative frequency distribution for the fatigue life at different S_{max} and found that the standard deviation of the number of cycles increased with decreasing stress level. Holmen suggested that the assumption of a linear relation in S-N curve is incorrect, meaning that a non-linear relation is more accurate in fatigue life prediction. Moreover, to establish a well-fitted regression line in S-N curve, the point of zero cycles does not necessarily reflect the real condition [19] and makes the conventional S-N curve slightly more inaccurate.

In one of the early investigations concerning the effect of stress gradient on fatigue life of concrete, Ople and Hulsbos [36] found that S_{max} and load eccentricity are two sensitive influential factors in determining fatigue life. They concluded that the uniform loading with no eccentricity is most damaging, while an increase in eccentricity is beneficial for fatigue life. Their results are in agreement with the findings from Cornelissen [37], who focused on the tensile fatigue behavior of concrete. Cornelissen concluded that stress gradient increases fatigue capacity and referred to the explanation of this phenomenon given by Dillmann [38]. According to Dillmann, an applied stress gradient causes a strain gradient, which leads to stress relaxation in some fibers in concrete and redistribution of them to less strained fibers. This effect is relevant for both tension and compression [37].

It has been surmised that different loading cycle regimes lead to different failure mechanisms. The dominant mechanism for low-cycle fatigue (higher stress level) is the formation of mortar cracks that leads to continuous cracked networks. On the contrary, high-cycle fatigue (lower stress level) produces bond cracks in a gradual and slow process [39].

2.5 Stress range

Stress range, or amplitude, is an important factor to separate sustained and fatigue load effects. In fatigue of concrete, it is common to express different stress ranges through the stress range ratio, $R = \frac{S_{min}}{S_{max}}$. Stress range and its influence are included in most of the fatigue studies. The effect of stress range in concrete is similar to a variety of materials such as steel. This means that an increase in stress range, both in compression and tension, tends to reduce the fatigue capacity [20, 35, 40, 41]. In one of the early studies in 1958, Murdock and Kesler [40] investigated the influence of stress range ratio on plain concrete beams subjected to cyclic bending loads. According to Figure 5, they found a clear relationship between stress range ratio and fatigue life, as it was described above.

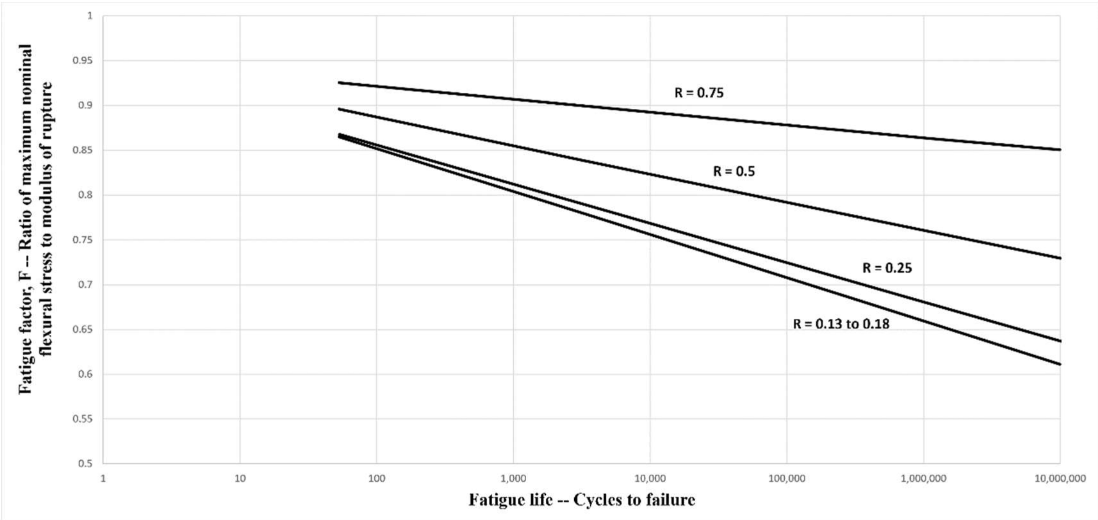

Figure 5 - Effect of stress range on fatigue life in compression loading [40]

Several studies [18, 37, 42] expanded the investigation of stress range into stress reversal, where the loading becomes an alternating tension-compression loading. In 1982, Tepfers [42] hypothesized that the degradation of concrete in tension and compression loading is different due to the crack propagation in opposite direction. Tepfers tested the hypothesis on 56 concrete cubes. The cubes exposed to stress reversal showed more scatter than the pure compression cubes. Tepfers attributed the scattered results to the tension loading arrangement; arrangement of tension loading setup is more challenging in achieving uniform loading than compression loading. Tepfers was not able to explicitly show that tension and compression degrade differently, and consequently, the effect of stress reversal remained uncertain. Cornelissen [37] and Zhang et al. [18] concurred that stress reversals give some reduction of fatigue life, though the effect is limited. The reduction in capacity is more significant with large amplitudes in the range of $0<R<1$.

2.6 Multi-axial stress states

There is a lack of research on the fatigue behavior of concrete under a multi-axial stress state. The multi-axial stress state can be divided into two groups: active confinement, caused by an external load to restrict the transverse strain, and passive confinement, which is the consequence of specimen's restraints and Poisson effect. Comprehensive understanding is required for both situations, as numerous structures face both passive and active confinement. Active confinement pressure is observed in prestressed structures that are exposed to excitation, while passive confinement occurs in the presence of physical restraints.

The specimens under confinement pressure have shown to obtain an increase in static strength as the failure mechanism changes from a brittle to a ductile failure [43]. In the early studies, the effect of passive confinement in fatigue applications was investigated by Desayi et al. [44] and Shah et al. [45]. They studied the effect of fatigue loading on concrete confined by passive spiral steel, and the stress-strain relationship from fatigue tests was compared to the static tests. Although the cyclic loading obtained slightly higher displacements than monotonic loading in certain conditions, they suggested that the passive confinement has a similar effect on the static and fatigue strength. Buyukozturk and Tseng [46] reported that lateral confinement induced higher stiffer behavior than that obtained by a uni-axial condition in the inelastic ranges. They also indicated how an increasing confinement load increases the failure strains. Hooi [47] performed fatigue loading tests on concrete cylinders with different amounts of passive confinement in the form of different amounts of steel spirals. According to Figure 6, Hooi concluded that the strength increases with the increasing amount of spiral reinforcement, which corresponds to f_l' ; however, this also resulted in a steeper S-N curve, meaning a faster degradation of fatigue life per cycle. In addition, the difference diminishes with high number of cycles.

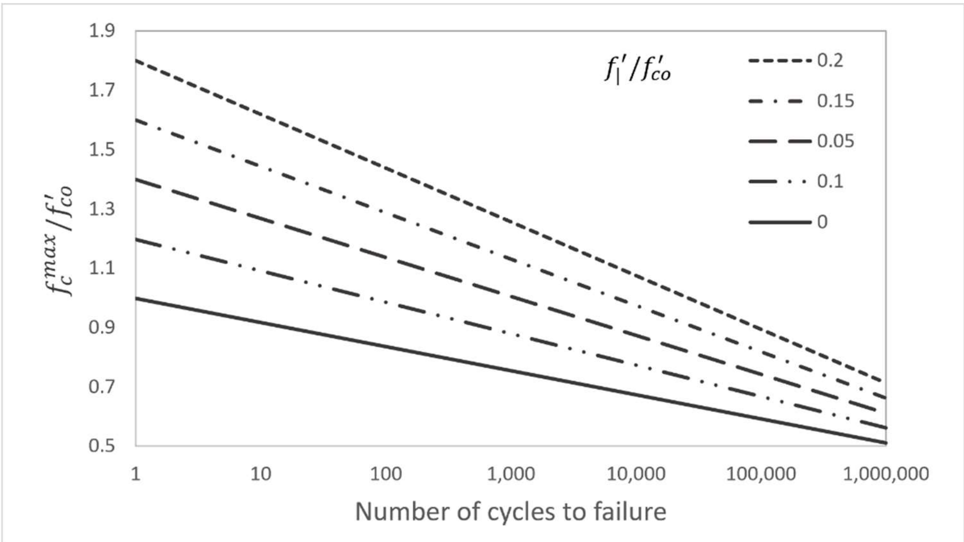

Figure 6 - Proposed S-N curve with different amount of lateral confinement [47]

Takhar et al. [48] investigated the effect of active confinement on the fatigue life of concrete. They reported that an extension of fatigue life corresponds to specimens with confining pressure, though this was only true at the stress level of $S_{max} < 0.9$ and for the higher stress levels, no noticeable difference was detected. In the mentioned studies, fatigue loading was only applied along one axis. Traina and Jeragh [49] studied the fatigue loading along more than one axis. Their setup tests consisted of four types of bi-axial fatigue loading on concrete cubes, (1) $\frac{\sigma_2}{\sigma_1} = 1$: both loads are cyclic; (2) $\frac{\sigma_2}{\sigma_1} = 0.5$: both loads are cyclic; (3) σ_1 is cyclic and σ_2 is constant at 6.9 MPa; (4) σ_1 is cyclic and σ_2 is constant at 13.8 MPa. σ_3 remained unloaded for all the tests. They found that setups (3) and (4) behaved similarly to the first two setups. In addition, an increase in strength was observed in all the cases compared to uni-axial loading. Takhar et al. found that fatigue loading with tri-axial confining stress causes longer fatigue life compared to a bi-axial confining stress state. The major discrepancy in their results was that Traina and Jeragh found a beneficial effect of increasing the confining stress from 6.9 to 13.8 MPa. On the contrary, Takhar et al. found a reverse relation, though both confining stresses caused an increase in fatigue life compared to uni-axial case. The explanation of this discrepancy is hard to determine as it needs an exact examination of the cause in the concrete specimens.

In the applications where the cyclic loading is applied in a compression-tension or pure tension format, the confining pressure has been shown to decrease the fatigue life. Song et al. [50] exposed concrete prisms to a cyclic tension-compression loading with active confinement at various levels. As seen in Figure 7, the results indicated a decrease in fatigue capacity with increasing confining pressure. In addition, Wang and Song [51] with a similar test setup showed that concrete prisms exposed to pure cyclic tension and active confinement yielded higher fatigue life compared to the tension-compression test setup, though the confining pressure was found to be disadvantageous in both tension and tension-compression cases.

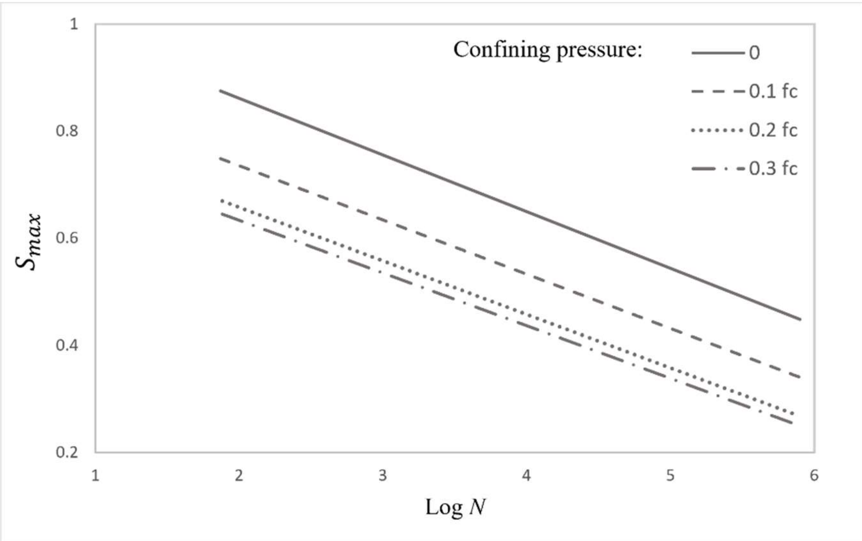

Figure 7 - Effect of various active confinement on tri-axial stress state of tension-compression loading setup [50]

2.7 Resting period

The knowledge of strength recovery in-between cyclic loading is limited to just a few studies. In one of the early studies, Hilsdorf [2] used a loading program of 4500 triangular load cycles before resting periods with the duration of either 1, 5, 10, 20 or 27 minutes. Hilsdorf noticed a rather small positive effect of rest periods up to 5 minutes in increasing fatigue strength and no extra contribution above 5 minutes.

Based on the findings by Murdock [52], Neville [53] reported a proportional relation between the increase of strength and rest duration up to 5 minutes with dependency on loading frequency. Neville explained this phenomenon as the result of the relaxation of concrete (relaxation of intermolecular bonds), where these unbroken bonds may return to their original state. In another study, Mallett [54] explained this as the result of stress redistribution and strain reversal that give an increase in fatigue life.

On the other hand, some other studies have found the rest period to have either a negative or neutral effect on fatigue life [55, 56]. Farhani [55] investigated the effect of rest periods on lightweight and normal concrete cylinders submerged in water with two different pressure states. One state with almost no confining pressure from the water while the other had 7 MPa. S_{max} and S_{min} were set to 0.7 and 0.05, respectively, with a 1 Hz sinusoidal loading waveform. It was found a decreased in fatigue life as a consequence of resting period. Although both LWA and normal concrete showed the same tendency, the fatigue life of LWA concrete was especially influenced by rest periods when water pressure was large. The resting period in this experiment was rather large (600 seconds), and the choice was based on the results from Viswanathan [56], who conducted a similar experiment with resting periods of 9 and 99 seconds and reported no effect of the resting periods. Farhani assumed that an increase in water ingression during a relatively large resting period would result in decreasing the fatigue life. Understanding the complexity of the interaction between water and the rest period in fatigue performance requires further investigations.

2.8 Loading time

In order to do a practical fatigue experiment, researchers are forced to alter the test parameters, such as the frequency of loads, as discussed previously. It cannot be denied that time complicates many investigations since concrete properties such as creep change with time due to moisture content, hydration, corrosion, etc. Consequently, the effect of time is of great interest to translate the results of short-time tests into real long-duration cases. Creep can develop as the concrete ages. Creep is of interest to designers since it influences deformation, which is one of the indicators of fatigue life consumption. Generally speaking, creep is defined as the increase of strain development due to the continuous loading or self-weight [57]. This phenomenon consists of recoverable and unrecoverable parts. The creep and its relation to cyclic loading were investigated by Whaley and Neville [58]. They investigated the issue of cyclic creep under various stress ranges and stress means. They found that by decreasing the range of stress level below 0.4 with constant mean stress of 0.35, the creep decreases uniformly. However, for stress ranges above 0.4, the creep increases severely. They also considered the cyclic creep to have two constituents; (1) the stress range component that causes creep from the cyclic loading amplitude, and (2) the mean stress component that causes creep from a static loading at the mean stress component σ_{min}. The comparison of the aforementioned constituents is shown in Figure 8. Since the creep ratio, a ratio of the range-of-stress component of creep to the static creep component decreased with time, Whaley and Neville concluded that the creep resulting from cyclic loading did not contribute to the overall creep observed under static loading conditions. Rather, cyclic loading led to an acceleration of the creep phenomenon. Their conclusion was supported by Zažant and Kim [59]. In a more recent study by Hümme et al. [31] a significant amount of strain due to time effects were verified by an experimental fatigue test performed on concrete cylinders with two different frequencies of 1 and 10 Hz and aging from 43 to 149 days. The strain value due to the time difference was found by subtracting the amount of strain accounted for temperature as well as creep autogenous deformation. The difference in temperature was reported between 20 to 25 K. Hence, assuming a thermal coefficient of $10^{-5}\,\frac{1}{\mathrm{K}}$, temperature difference only accounts for 0.02 % – 0.025 % of the strain out of 0.082 %.

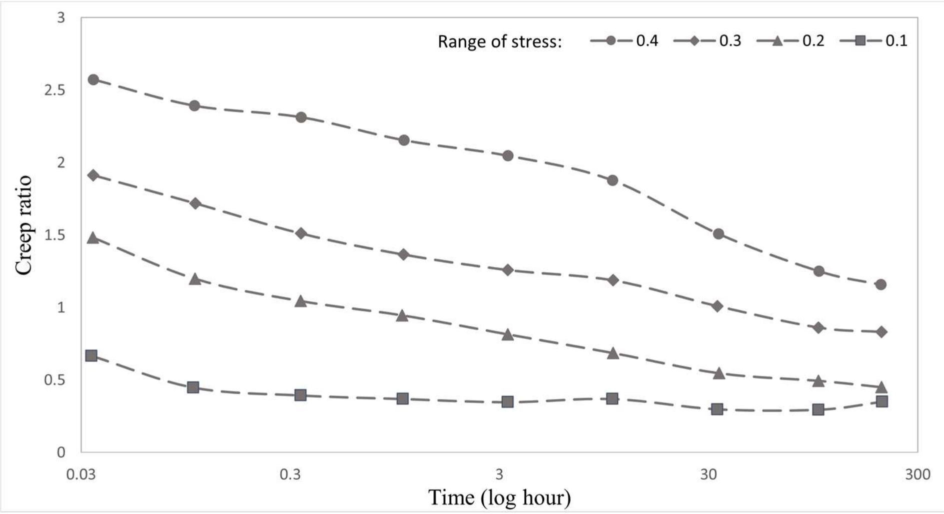

Figure 8 - Effect of range of stress upon the ratio of the range-of-stress component of creep to the static creep component [58]

3 FATIGUE LIFE PREDICTION

The heterogeneity of concrete material and its complex behavior upon cyclic loading makes the fatigue life prediction of concrete difficult. This section presents a review of the fatigue life prediction models of concrete. In general, there are five different approaches to evaluating the fatigue life of a structural element that the review elaborates on: S-N curve method, P-M rule, fracture mechanics method, continuum damage mechanics method, and artificial intelligence.

3.1 S-N curve method

This approach shows the relationship between fatigue stress and fatigue life. The S-N curve method is based on the empirical formula and regression analysis from fatigue stress life data of concrete at varying stress levels. This approach considers overall fatigue life and suffers from lack of non-linearity behavior, heterogeneity of concrete and inability to consider the brittle failure of concrete. Because of high variability in fatigue test data, probability analysis was introduced to estimate the fatigue life of concrete and concluded that the S-N curves are somewhat valid for the prediction of fatigue life for stress level range of 65 to 85 % [60]. Holmen [17] observed that the S-N curve method is not reliable to evaluate the fatigue fracture of plain concrete under constant and variable amplitude cyclic loading.

3.2 Palmgren-Miner rule

The Palmgren-Miner (P-M) rule, also known as Miner's cumulative damage hypothesis, provides a method to evaluate the cumulative damage in a material subjected to repeated loading [28]. It involves summing the fractions of fatigue life consumed by each load cycle. According to the rule, damage accumulation is assumed to be linear and directly proportional to the number of cycles, with each cycle contributing independently to the overall damage. If the cumulative damage exceeds a predetermined threshold (often set at 1 or 100% fatigue life), it indicates a higher likelihood of fatigue failure. Conversely, if the cumulative damage remains below the threshold, the component is considered to have an acceptable fatigue life. The P-M rule is represented by Equation 2, where n_i denotes the number of cycles applied to a specific stress block, N_i represents the number of cycles that can be sustained by the same stress block, and D signifies the cumulative damage.

$$D = \sum_{i=1}^{i} \frac{n_i}{N_i} \leq 1 \tag{2}$$

3.3 Fracture mechanics method

The fracture mechanics approach considers the failure mechanism of the material by crack initiation and propagation. This method depends on the stress intensity factor, which is a function of crack length and stress state [61]. This method considers the condition around the crack tips and the crack growth due to the cyclic load as the failure criterion. Paris law defines the relationship between the amplitude of stress intensity factor and crack length increment per cycle. The formulation of this relationship is given by:

$$\frac{da}{dN} = C(\Delta K)^m \tag{3}$$

Where a is the crack length, N is the corresponding load cycles, ΔK is the amplitude of stress intensity factor and m and C are the material constants [62]. Nevertheless, the Paris law is only valid for macroscopic cracks in large specimens and is incompatible with heterogeneous materials. Paris law was adjusted by Bažant and Kazemi [63] to include the size effect, and crack length increment depends on size adjusted stress intensity factors:

$$\frac{da}{dN} = C(\frac{\Delta K}{K_{Ic}})^m \tag{4}$$

$$K_{Ic} = K_{If}(\frac{\beta}{1+\beta})^{1/2} \tag{5}$$

Where fracture toughness K_{If} is the value of K_{Ic} for an infinitely large specimen, and β is brittleness number (ratio of structure size D to transitional size d_0; experimentally found that d_0 for cyclic loading is much greater than corresponding value for monotonic loading [63]). The cyclic tests conducted on a single edged notched beam element inferred that Paris law could be applied for crack growth in plain concrete [64]. The stability of fracture process for reinforced concrete beams could be accomplished when the beam has sufficient reinforcement [65]. Although the prediction of fatigue life of concrete has been achieved through the fatigue crack propagation law, the varying parameters make the use of the method complex and not dependable.

3.4 Fatigue damage mechanics models

There are two approaches in fatigue damage mechanics, the continuum damage method, and the energy dissipation method.

Continuum damage models

The degradation of the bond between the cement matrix and aggregate and the damage of material grains affect the elastic properties of concrete, which makes it anisotropic. The micro-cracks and void progression are the main reason for this destruction and nonlinearity in concrete. The damage of the anisotropy material can be utilized for the development of Continuum Damage Models [66]. By applying thermodynamics theory and dissipation function, the growth rate of damage was evaluated, and a damage evolution model was developed with respect to thermodynamic force conjugates of the variables of the damage [67]. This model, which is a nonlinear damage model, is able to predict the fatigue life under compression load for a specific range of concrete strength.

Energy method
Throughout the loading process of concrete, there is an exchange of energy with the surrounding environment. The entire energy dissipation from the system can be divided into heat energy and the loss of energy due to material damage. The energy required during crack propagation, plastic strain energy, and defect formation are the main energy dissipation due to material damage. Thus, based on the degree of material damage and the energy dissipation trends, the damage evolution law of material and its fatigue life prediction were obtained [68]. An equation to determine the fatigue failure of concrete based on the stability of the mono-cycle energy dissipation and uniformity of the critical energy dissipation was proposed by Lei et al. [69], nevertheless, the method is only valid for viscoelastic concrete material and is not applicable for ordinary concrete material due to its quasi-brittle behavior.

3.5 Artificial intelligence

The application of artificial intelligence in the fatigue life prediction of concrete elements has been focused on and studied in recent years [70-75]. Artificial neural networks (ANNs) constitute a class of computational tools that were inspired by the biological nervous system. By using ANNs, complex relationships between inputs and outputs can be modeled. For instance, the compressive strength of concrete was shown to be predicted better with ANN models than the traditional methods [71]. This was also the same case for the prediction of the number of reversals to fatigue failure of steel reinforcement bars that ANN gave a more accurate prediction [72]. An ANN model was utilized for the prediction of the fatigue endurance limit of conventional asphalt concrete pavements [73]. Zhang et el. [75] proposed a machine learning-based fatigue crack growth detection method that combines computer vision for crack path and length analysis. In this method, a generalized and reliable model for the prediction of fatigue life of concrete is yet to be established. Abambres and Lantsoght [74] gathered 203-point experimental dataset from literature to develop an ANN model that predicts the reduced compressive strength of concrete under fatigue compression. They reported that their proposed ANN model outperforms three design code formulation: Dutch national code *NEN 6723:2009* [76], *Eurocode 2* [77], and the *fib model code 2010* [78]. further experimental results on high-cycle fatigue need to be gathered to broaden the scope of their proposed model, which perhaps gives a highly robust prediction model.

Although artificial intelligence depends on historical experimental data for training purposes, it has demonstrated superior performance compared to empirical approaches like S-N curves commonly used in design codes. Furthermore, AI offers several advantages, including the ability to be regularly updated with recent experimental data, the incorporation of multiple parameters as inputs to the model, and the potential for increased accuracy with advancements in machine learning models in the future.

4 DESIGN APPROACHES

This section introduces some design rules of fatigue and improvements suggested by researchers in the field. In this part, three well-known standard codes are compared based on their design approach for fatigue life prediction of concrete elements.

Eurocode 2 [79], one of the main providers of design rules, has simplified the fatigue treatment to ensure safety and mainly bases it on S-N curves that are generated by regression curves from data obtained by testing plain concrete cubes and cylinders. In the case of concrete fatigue, the *Eurocode* does not have a method of measuring fatigue life. Instead, the code verifies that the concrete can withstand a given number of cycles, typically 10^6 cycles. The code does not consider the environmental condition the structure is exposed to.

DNV-OS-C502 [77] is the only code among others that takes the environment into account. This means that the concrete specimens exposed to water during their life use a lower constant value in the formulation of fatigue life prediction. Therefore, the fatigue life will be estimated lower compared to those in a dry/aired environment. However, the water content of the specimen itself is not considered, meaning that aired and sealed structures are considered equal, which is not correct. Similar to the *Eurocode 2*, *DNV* bases fatigue life estimation on S-N curves that are generated from empirical formula.

fib Model Code [78] is a source of design code provided by *fib* (Federation internationale du beton). The *Model Code 2010*, the most current published model code, includes an update for the fatigue section based on Lohaus et al. [80]. The main contribution was a fatigue model for ultra-high strength concrete (UHPC). The updated S-N curves account for fatigue life estimation using the same parameter as the *Eurocode*. Besides, both the *Eurocode* and *Model Code 2010* utilize the P-M rule to account for variable amplitude stress blocks, though the P-M rule is not consistently applicable to concrete. For reinforcement and prestressing steel, the rules are only applicable for high cycle fatigue, which is more than 10^4 repetitions. The verification can be performed with four different methods with increasing refinement. The *fib Model Code 2010* incorporates the use of S-N curves and includes a dedicated table for reinforcement to determine the characteristic fatigue strength. However, it is important to note that the code does not explicitly account for the influence of reinforcement. As a result, the static strength outlined in the code primarily relies on the properties of the concrete, with the failure of plain concrete considered as the governing factor.

The treatment of variable stress blocks (amplitude loading) and the sequence effect are the main gaps between design methods and real-life tests, though the other effects influencing fatigue life could potentially be accounted for by using certain coefficients. As an example, in offshore structures, the dynamic excitation for fatigue is mainly wave and wind loads. These loads must be considered in an integrated non-linear time domain simulation where the loading from waves and the wind is generated simultaneously to account for the coupling between hydrodynamic are aerodynamic responses. The consensus among several researchers is that the solution for the aforementioned complexity of loading possibilities for fatigue design lies in analytical methods rather than empirical ones. Further, two main analytical approaches are introduced.

4.1 Nonlinear damage approach

The curves for deformation, acoustic emission, and ultrasonic pulse velocity display a pattern with three distinct stages, indicating that damage accumulation and strain evolution in concrete are nonlinear. As a result, many attempts to replace the P-M rule rely on a nonlinear damage accumulation method. Baktheer et al. [81] attempted to address this issue by adjusting the P-M rule to incorporate nonlinear damage development and the sequence effect. This approach employs a numerical model developed by Alliche [82], which employs damage mechanics to describe damage accumulation. However, due to the need for a comprehensive explanation of continuum mechanics, a detailed explanation of this three-dimensional model is not provided in this review.

Baktheer's model is utilized to estimate the outcomes of both Schneider et al.'s [83] single amplitude tests and Holmen's [17] two-stage loading experiments. Using the straightforward pattern observed in the sequence effect, Baktheer suggested an improved damage accumulation principle that remains heavily reliant on the P-M rule. This proposed rule involves the addition of an extra term to the P-M rule, demonstrated in Equation 6:

$$\eta = \sum_{i=1}^{n} \eta_i + \sum_{i=1}^{n-1} \Delta\eta_i \qquad (6)$$

Similar to the P-M rule, at η = 1 failure occurs. The first term in the formulation $\eta_i = N_i/N_{if}$ is unchanged from the P-M rule. The second term of the equation considers the impact of the sequence effect and the nonlinear accumulation of damage. It incorporates multiple factors, as demonstrated in Equation 7:

$$\Delta\eta_i = R(\bar{S}_i, \Delta S_i^{max}, \Delta S_i^{mi}\ , \tilde{\eta}_i) \qquad (7)$$

Where the coefficients of $\Delta\eta_i$ were obtained through simulations of data and certain approximations. The outcome was an improved damage accumulation principle that corresponds well with the findings of Alliche's model, as anticipated since the rule was calibrated to approximate it. Nonetheless, the improved P-M rule provides a straightforward means of assessing damage caused by fatigue. Nevertheless, additional validation is necessary for both Alliche's model and the enhanced P-M rule.

Baktheer et al. [81] made an assumption that the nonlinear damage curves for various loadings can be added together, which has been assumed for several decades but has not been put into practice. In 1986, Lenschow [84] assessed the Norwegian rules for fatigue design and briefly discussed the P-M rule. At that point, it was recognized that strains might be a useful indicator of damage. Moreover, it was believed that damage propagation from multiple-stage loading would follow the strain curves. A change in the load led to a shift in the strain curve for the following loading at the cumulative value of ε.

The problem with designing for damage accumulation is the insufficient amount of experimental tests to validate analytical models. It would require a significant amount of effort to conduct a purely experimental confirmation of load combinations.

4.2 Deformation design approach

Study of concrete deformation to ensure that the element remains suitable for its intended application might be as equally important as focusing on the ability of concrete to withstand cyclic loading. As shown in Equation 8, *Model Code 2010* [78] offers a simple method to approximate the deformation from fatigue loading.

$$a_n = a_1[1.2 - 0.5e^{-0.03n^{0.25}}] \quad (8)$$

where a_n is the deflection after n loading cycles and a_1 is the initial deflection after first cycle caused by the maximum load. The formulation does not consider enough variables; hence, a higher conservative result may be expected due to the complexity of concrete's nature. The estimation of deflection and strain development is a complicated matter. As described earlier, the strain development of fatigue in concrete tends to follow the three-phase s-curve shape through the lifespan (as seen in Figure 9), and the duration of each phase changes with the concrete strength. An extension of phase two is an indication of increased fatigue life [24]. The lifespan of most structures is designed to stay away far from a state of fracture where it happens in the last phase, hence, the strain development in phase two is of primary interest. It is hard though to efficiently approximate the contribution of different strains such as plastic strain, creep effect, strains due to cyclic effect, and elastic strain in the total strain. Evidently, the rules of fatigue design are greatly simplified, and as a result, the need for a safe design has forced engineers to apply conservative approach.

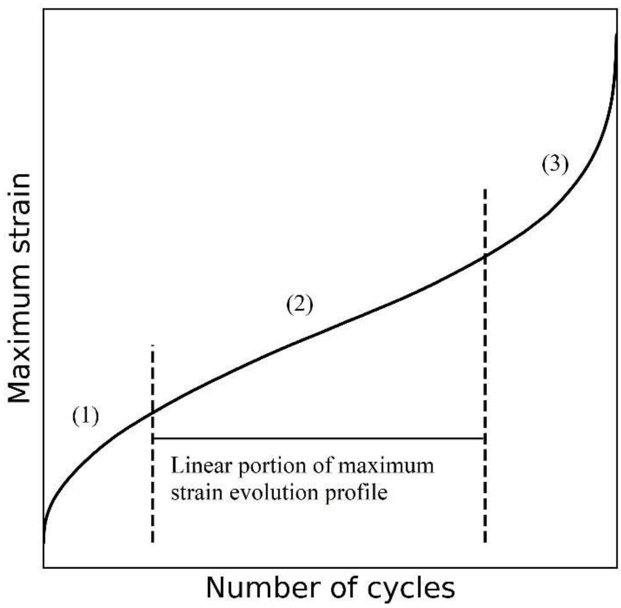

Figure 9 - Three-phase s-curve shape of strain evolution through the lifespan

5 CONCLUDING REMARKS

Several studies have reported different factors affecting the fatigue performance of concrete, and most of these factors tend to interact. Consequently, it is difficult to consider the effect of each factor as a separate entity. In addition, due to the complexity of the fatigue behavior of concrete, more research is needed in each phase of fatigue, and further investigations must be well organized in a way to isolate a particular factor.

The lack of a well-established test procedure for executing fatigue tests makes it difficult to correlate published test results, and in some cases, there is conflicting information in the literature. Hence, systematic comparison and analysis have shortcomings and difficulties due to the variation in test parameters.

The development of our knowledge regarding the fatigue mechanisms is essential as it might help to transit from empirical formulas to analytical solutions. Consequently, the development could also improve design codes and allow them to include several influential factors in addition to number of load cycles, stress level and loading amplitude, which are the main current factors used in the design codes. In conclusion, as the material develops, our understanding of fatigue mechanisms also may change, and so does the design codes; hence, there is a vast potential for further development and investigation of fatigue in concrete.

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