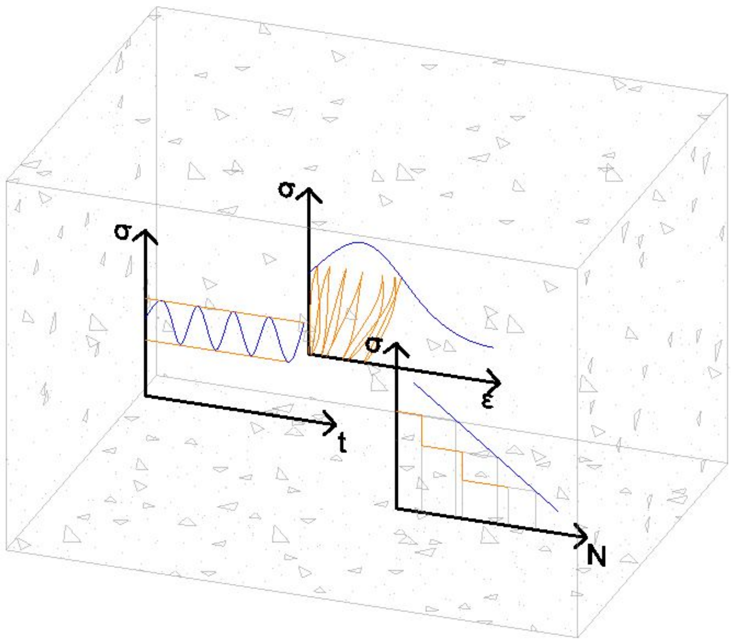
Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Structural Engineering

Thomas Hollekve Paulsen

Fatigue of Concrete

Master's thesis in Bygg- og miljøteknikk
Supervisor: Jan Arve Øverli
June 2021



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Fatigue of Concrete

Utmatting av Betong

BY:

Thomas Hollekve Paulsen

SUMMARY:
The continuous improvement of concrete as a material, combined with an increasing desire to construct material efficient structures, lead to slender structures. This slenderness tends to increase the importance of cyclic loading, and possibly make fatigue the governing design criterion. Further development of fatigue design is needed to avoid this restraining the structure from reaching its potential.
The fatigue phenomenon is also of great interest with respect to prolongation of existing structures, such as offshore structures already exceeding their intended service life.

This thesis highlights the knowledge concerning concrete fatigue available through the literature. Hence, it will serve as a summary of the current state of knowledge, but also reveal the areas needing further attention. This is achieved by reviewing different factors influencing the fatigue performance of concrete. The contrast between design rules and the knowledge available through literature is also highlighted to some extent. The influencing effects found in plain concrete are presented through 15 factors.

Due to the wide variety of testing setups, a quantification of the degree of influence for the different factors is difficult. This partly explains the simplifications of fatigue treatment done by the Eurocode. The Eurocode only explicitly accounts for stress level and amplitude, while the remnant factors are conservatively treated by a further reduction of strength compared to the "normal" design strength. Despite the difficulty of determining the most influencing factors, there are certain clearly visible discrepancies between design and test results. The treatment of damage accumulation is especially in need of further investigations due to the large uncertainty of what constitutes a safe approach.

RESPONSIBLE TEACHER: Jan Arve Øverli

SUPERVISOR(S)

CARRIED OUT AT: Institutt for Konstruksjonsteknikk

Abstract

The continuous improvement of concrete as a material, combined with an increasing desire to construct material efficient structures, lead to slender structures. This slenderness tends to increase the importance of cyclic loading, and possibly make fatigue the governing design criterion. Further development of fatigue design is needed to avoid this restraining the structure from reaching its potential. The fatigue phenomenon is also of great interest with respect to prolongation of existing structures, such as offshore structures already exceeding their intended service life. This thesis highlights the knowledge concerning concrete fatigue available through the literature. Hence, it will serve as a summary of the current state of knowledge, but also reveal the areas needing further attention. This is achieved by reviewing different factors influencing the fatigue performance of concrete. The contrast between design rules and the knowledge available through literature is also highlighted to some extent. The influencing effects found in plain concrete are presented as the following 15 factors:

- Stress Level
- Concrete Composition
- Loading Rate and Frequency
- Loading Waveform
- Moisture
- Rest Periods
- Stress Gradients
- Size Effect
- Amplitude and Stress Reversal
- Multiple Stage Loading
- Temperature
- Time
- Multiaxial Stress State
- Reinforcement
- Sea Water

Due to the wide variety of testing setups, a quantification of the degree of influence for the different factors is difficult. This partly explains the simplifications of fatigue treatment done by the Eurocode. The Eurocode only explicitly accounts for stress level and amplitude, while the remnant factors are conservatively treated by a further reduction of strength compared to the "normal" design strength. Despite the difficulty of determining the most influencing factors, there are certain clearly visible discrepancies between design and test results. The treatment of damage accumulation is especially in need of further investigations due to the large uncertainty of what constitutes a safe approach.

Sammendrag

Stadige fremskritt innenfor betongteknologi muliggjør bygging av slankere og mer materialeffektive konstruksjoner enn tidligere. Ved økt slankhet blir også påvirkningen fra sykliske laster viktigere og utmattingskapasiteter kan bli dimensjonerende. Å kunne dimensjonere med minst mulig feilmargin blir da viktig for å unngå at utmatting forhindrer full utnyttelse. For å oppnå dette behøves det ytterligere fremskritt innenfor utmattingsfenomenet. Ny kunnskap på dette feltet er også av stor interesse for å forlenge levetiden til eksisterende konstruksjoner, for eksempel offshore konstruksjoner som allerede har passert sin dimensjonerte levetid. Denne masteroppgaven består av et litteraturstudium hvor dagens kunnskap rundt temaet "Utmatting av Betong" belyses. Det er spesielt lagt vekt på hva som påvirker utmattingskapasiteten til "ordinær" betong. En kort gjennomgang av dagens regelverk er gitt og sammenlignet med litteraturens standpunkt. Påvirkningsfaktorer funnet i litteraturen er inndelt i følgende 15 faktorer:

- Spenningsnivå
- Betongsammensetning
- Lastrate og frekvens
- Lastform
- Fuktighet
- Hvileperioder
- Spenningsgradient
- Størrelse
- Amplitude og spenningsreversering
- Flerstadiumslaster
- Temperatur
- Tid
- Multiaksiell spenningstilstand
- Armering
- Sjøvann

På grunn av mange forskjellige testparametre er det vanskelig å fastslå påvirkningen fra hver faktor. Dette forklarer delvis hvorfor Eurokoden forenkler behandlingen av utmatting. Eurokoden tar kun eksplisitt hensyn til spenningsnivå og amplitude, mens øvrige faktorer håndteres ved ytterligere reduksjon av dimensjonerende fasthet. Til tross for utfordringene med å fastslå hvor mye hver faktor påvirker, er det likevel noen faktorer som viser stort potensial for forbedring av dimensjoneringsregler. Dette gjelder spesielt ved håndtering av skadeakkumulering, hvor det er stor usikkerhet knyttet til hva som ansees som en konservativ tilnærming.

Contents

List of Abbreviations and Notations

Abbreviations

$E_{cd,max,equ}$	Maximum relative stress level
CMOD	Crack mouth opening displacement
HSC	High strength concrete
LWA	Lightweight aggregate
MOR	Modulus of rupture
NDC	Normal density concrete
NSC	Normal strength concrete
P-M rule	Palmgren-Miner rule: Linear accumulation law for fatigue damage
UHPC	Ultra high strength concrete
w/c ratio	Water-cement ratio

Notation

Δ	Cyclic stress range (Amplitude)
δ	Crack mouth opening displacement
ω	Damage parameter for concrete
σ	Applied stress
$\sigma_I(x)$	Assumed stress distribution in crack zone
$\sigma_{II}(x)$	Assumed stress distribution above crack zone
τ_{bond}	Shear stress between reinforcement and concrete
ε_f	Plastic strains due to cyclic loading
ε_{II}	The secondary strain gradient: Strain gradient in stage two of the strain development
ε_{meas}	Measured deformation due to cyclic loading
ε_{S_m}	Deformation due to static application of mean level from cyclic load
d_{steel}	Reinforcement diameter
E	Elasticity module measured from the unloading branch of the stress-strain curve

E_0	Initial elasticity module of a specimen
f	Ultimate static compressive strength
f_l	Effective lateral confining stress
f_q	Loading frequency [Hz]
f_{cc}	Confined concrete strength
f_{co}	Unconfined static concrete strength
F_{steel}	Force in reinforcement
K_1	Strength enhancement factor due to lateral reinforcement
L_{bd}	Anchor length of reinforcement
N_f	Number of load cycles at failure
N_i	Expected number of endurable cycles for a given load
R	$= \frac{S_{min}}{S_{max}}$ = Stress level ratio
R_{creep}	$= \frac{\varepsilon_{meas} - \varepsilon_{S_m}}{\varepsilon_{S_m}}$ = Ratio of creep from the stress range component to the mean cyclic loading component
S_m	Mean stress level of the cyclic loading
S_{max}	$= \frac{\sigma_{max}}{f}$ = Maximum cyclic stress level relative to static strength
S_{min}	$= \frac{\sigma_{min}}{f}$ = Minimum cyclic stress level relative to static strength
M	Applied external moment
n	Amount of cycles at a given time

1 Introduction

1.1 General

The continuous development of concrete and the desire to optimize our structures emphasize the need for more accurate design methods. This applies both in the design of new structures and with prolongation of existing structures. The increased optimization usually yield slender structures, highlighting the issue of fatigue. Especially offshore structures, which must endure significant cyclic loading throughout their lifespans, must be carefully designed with respect to fatigue. The fatigue phenomenon in concrete has received increased attention during the last 50 years, yet the design rules remain scarce. This scarceness is partly due to the lack of unified methods of testing to allow proper comparison, and partly due to the complexity of concrete fatigue behaviour.

The lack of accurate design methods for concrete fatigue also prevent optimization of the dynamic properties. The tuning of the natural frequencies of a construction in relation to the load frequencies, is vital in order to keep the loads at a minimum. In this way, the dynamic design is a part of the design criteria of a structure, where a perceived conservative design might prove to be the opposite. Hence, accurate and safe design of such loads depends on accurate and trustworthy methods of material behaviour. Historically, the need for dynamic design of concrete structures has been limited. However, fatigue is becoming increasingly important due to the large improvements in concrete qualities in recent years. The increasing attention towards an environmentally friendly and more sustainable construction industry forces designers to optimize and design slender structures. Consequently, structures such as windmills and to some extent bridges, are becoming more vulnerable to fatigue failure. Prolonging the lifetime of existing structures is also of great interest. Especially offshore oil platforms are approaching or have exceeded their intended lifespan. Many of them have been designed for a lifespan of 20-30 years, but are currently approaching 50 years. These massive constructions are however still in service, and there are great environmental and economical values in prolonging their intended service life. To achieve this, more accurate estimation methods are essential in order to quantify potential remaining lifetime.

The aim of this thesis is to highlight the available knowledge on fatigue of concrete, and summarize the various factors influencing fatigue capacity. Thus, it will provide an overview of the fatigue phenomenon in concrete and show some of the discrepancies between the design methods and experimental tests. The primary focus is the fatigue of plain concrete, but some issues with the presence of reinforcement is also included. Furthermore, some of the existing design rules are presented and the discrepancies between design rules and current knowledge are highlighted.

1.2 Structure of the Work and Limitations

This thesis is a literature study and will take the form of a traditional literature study[1]. This is considered to be most appropriate as the intention is to capture the broad variety of effects which may influence the fatigue performance of concrete. The large variation in possibilities of procuring literature makes detailed description of searches and methods of literature collection a time consuming and extensive event with little value for later work. As a result, such a description is omitted. Furthermore, this thesis is limited to plain concrete made with Portland cement and does not treat special subjects such as fiber reinforced concrete, self compacting concrete etc. The vast variation of concrete types with different characteristics would require several theses of their own to do the subjects proper justice.

2 Fatigue in General

Fatigue of concrete is a complicated subject. Concrete specimens often show conflicting behaviour, making generalizations difficult. Despite this, the current research share some trends. The following section will review some of the research which have defined our treatment and understanding of fatigue, as well as presenting the ”typical” behaviour of concrete fatigue.

2.1 Fatigue Fundamentals

The fatigue process is known as a progressive material deterioration which eventually leads to failure even at stress levels far below the static strength[2]. The rupture may come quite suddenly, depending on the material, and appears after a certain number of load cycles. This depends on several factors, which will be thoroughly discussed in this thesis.

The phenomenon of fatigue has been referred to long before the phenomenon was scientifically documented[3]. One of the first scientific investigations however was conducted by Albert[4] in 1837. He published a paper on conveyor chains which failed at loads below the characteristic strength. The next important fatigue issue concerned fatigue of railway cart axles, where the most significant breakthrough came in 1870. This was the contribution of Wöhler[5], who presented the Wöhler laws. His work has later been known as Wöhler-curves, a method of describing capacity of a member for certain loads, and is still used today. The Wöhler-curves are also frequently called SN-curves. In steel design, S stands for stress range while N is the number of cycles. In concrete applications, the name has remained unchanged, although the S stands for maximum stress level. This is because the main parameter for concrete is maximum stress level, while the amplitude seems the have the most influence for steel. The term SNP-curves, where P stands for probability, is also used. These curves are corrected for some uncertainties, and are important for materials such as concrete where the scatter from tests might be great. However, the term SN is often used even for SNP-curves. The SN-curves are usually plotted on a semi logarithmic plot due to the stress level being approximately linear to the logarithmic number of cycles. A typical SN-curve for concrete applications with the 95% confidence intervals is shown in Figure 1.

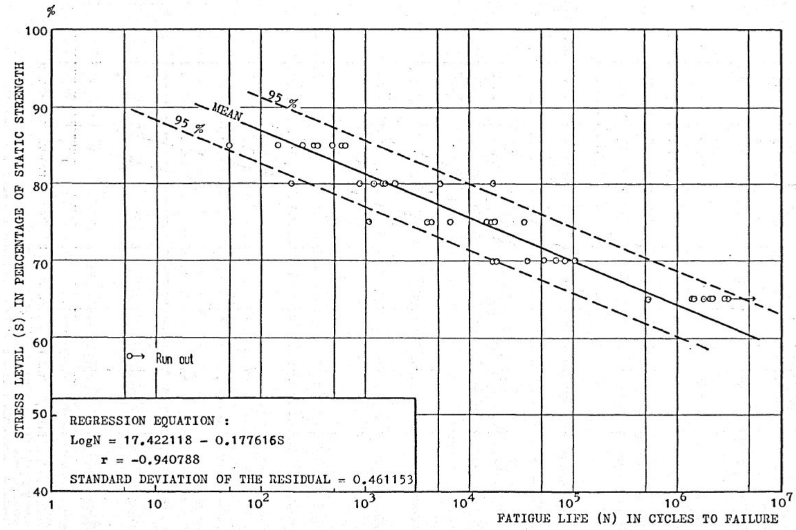


Figure 1: A typical SN-Curve with probabilistic methods included[6]

The SN-curves provide a good basis for fatigue life estimation due to single cyclic loads. The applicability of such curves when dealing with multiple cyclic loads has been, and still is, a subject of discussion. The most influential contribution to this issue came in 1924 and was the work of Palmgreen[7]. He formed the much-used linear damage accumulation rule. Later in 1945, Miner[8] continued this rule and supported the findings by experimental tests. The linear damage accumulation rule is also known as the Palmgren-Miner (P-M) rule. It is frequently being used in fatigue life determination for various materials, although its original application was for steel components. The P-M rule is defined as shown in Eq.1, with the number of applied cycles for a certain load as n_i and the number of endurable cycles for the same load as N_i. The damage (D) is usually calculated with the limit set to 1. The validity of this limit and the P-M rule in general is however under some scrutiny since the estimated fatigue life differs from the experimental results in some cases. This will be elaborated on further in Section 3.10 and 4.

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

The appliance of the P-M rule with the SN-curves is illustrated in Figure 2.

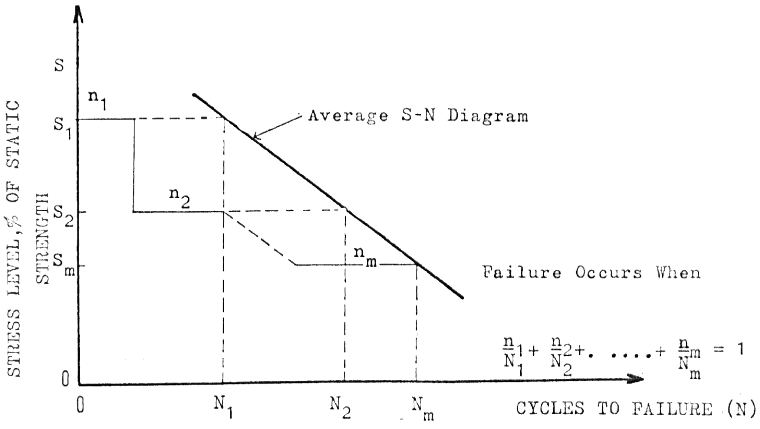


Figure 2: The P-M rule applied with SN-curve[6]

Even though concrete can be traced back 10 000 years[9] and an extensive amount of research has been performed on this material, concrete fatigue was not studied until recently. The issue of fatigue in concrete received its first contribution at the start of the 20th century by Van Ornum[10] and has subsequently slowly received increased attention.

The issue of fatigue in concrete is usually divided into two categories: High cycle and Low cycle fatigue. Some studies also define Super-high cycle fatigue, although this is usually treated as simply a case of High cycle. High and Low cycle fatigue typically constitutes fatigue failure above or below 10^3 cycles, respectively[11]. The reason for this distinction is based on the observation of significantly different behaviour of concrete specimens above and below this threshold. The categories also correspond to certain types of cyclic loading as seen in Figure 3.

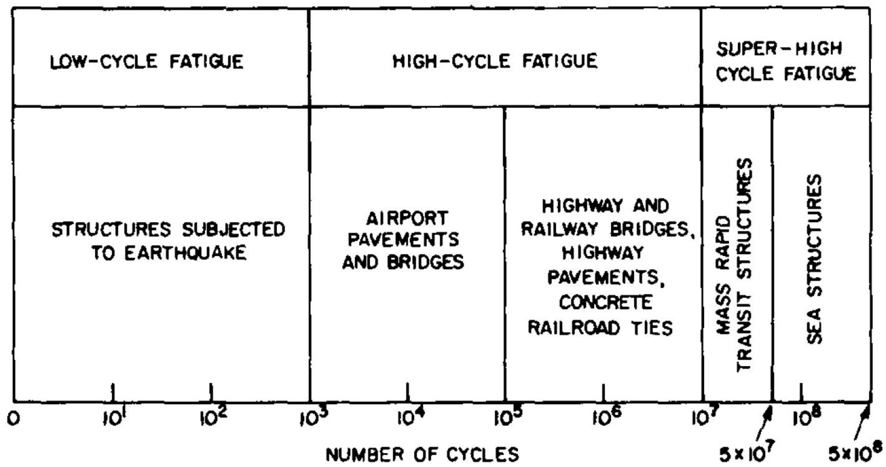


Figure 3: Fatigue categories, limits and corresponding loads/structures[11]

Whether a cyclic load will have the potential to induce a High cycle or Low cycle fatigue failure depends on several factors. For isotropic materials, the fatigue capacity depends mainly on the load amplitude, structural geometry and load cycles. For composite materials like concrete, correct estimation becomes more complicated. The microstructure of the material influences its resistance to fatigue. In general, the four constituents of concrete (cement, aggregates, water and additives) and its cast environments give large variation in the internal structure. This variation is often assumed to be the cause of large scatter in test results, both in cyclic and monotonic tests.

The lack of identifiable surface topology for concrete makes it more difficult to determine fatigue damage in concrete structures compared to steel structures[12]. Moreover, the variation caused by different concrete types, shapes, sizes, environments and curing conditions contributes to different fatigue properties. Due to the complexity of fatigue in concrete, a staggering amount of research has been done to develop design methods fitting the experimental results. However, no valid simple method seems to fit sufficiently for all cases and the lack of better methods have resulted in the adoption of SN-curves and the P-M rule.

2.2 Damage Development due to Fatigue of Concrete

The fatigue phenomenon in steel and other similar metals has been subjected to a large amount of research and is today quite well defined. Especially the fatigue failure pattern of steel is rather characteristic, and it is therefore simple to classify as fatigue failure. Steel fatigue failure typically has a smooth surface with concentric lines around its initiation point, where the final failure is either a brittle failure or a ductile yielding of a reduced cross section[13]. The fatigue failure of concrete is however not so well defined, and the exact point of failure is a subject of discussion. Despite the difficulty of characterization of fatigue in concrete, certain properties are still widely acknowledged. A clear surface topology is lacking from the concrete cross-section in which fatigue yielding occurs. The fatigue failure does however exhibit more extensive cracking compared to monotonic loading. This is illustrated in Figure 4. The fatigue process in concrete is generally attributed to be caused by development of internal microcracks in both the cement matrix/aggregate interface and in the matrix itself[14]. The presence of existing microcracks as a consequence of curing conditions is also thought to play a role[15]. The study of the fatigue process has been performed by several researchers with different methods, both in specimen type and in measuring. From these tests, a clear common trend in behaviour is found.

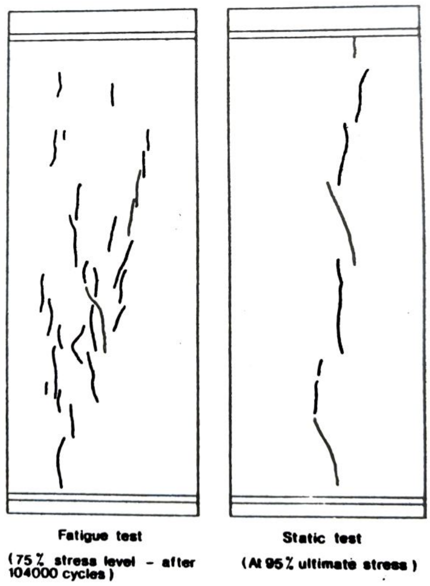


Figure 4: Comparison of crack growth from cyclic and monotonic load in compression [16]

Measurements of strains typically show a strain development consisting of three stages, as presented in Figure 5, and seems to hold for both longitudinal and transversal strains. For normal strength concrete (NSC), the three stages are normally defined as[17]:

Stage 1: Rapid strain development from 0 to 20% of the fatigue life

Stage 2: Linear strain development from 20 to 80% of the fatigue life

Stage 3: Rapid strain development from 80 to 100% of the fatigue life

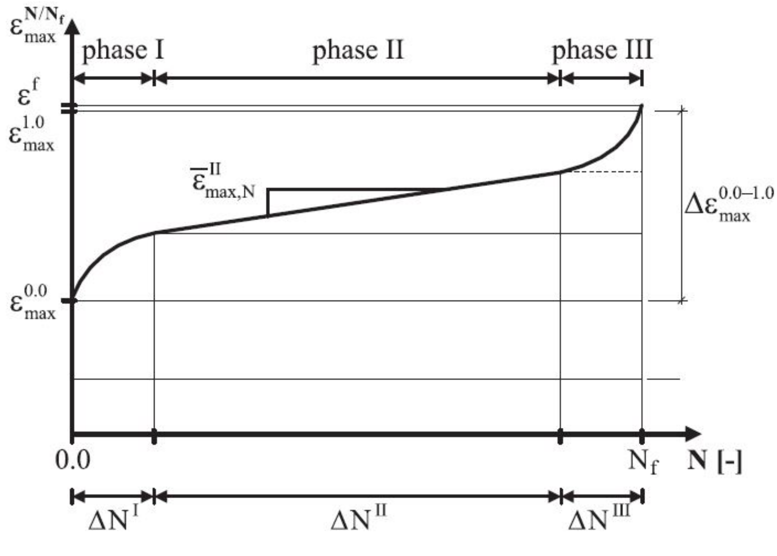
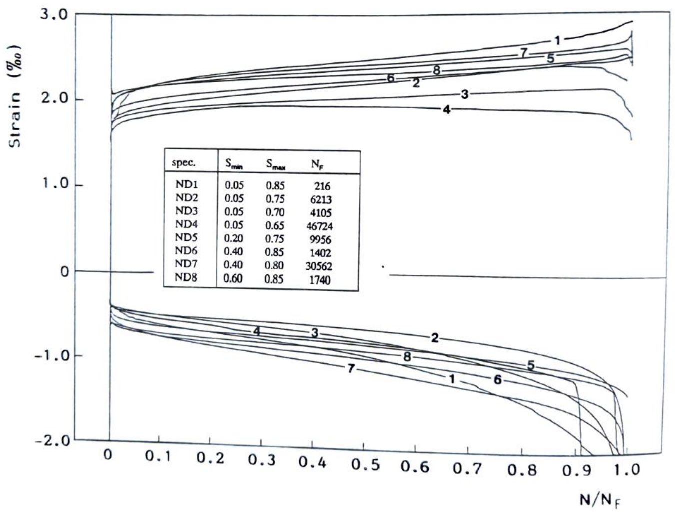
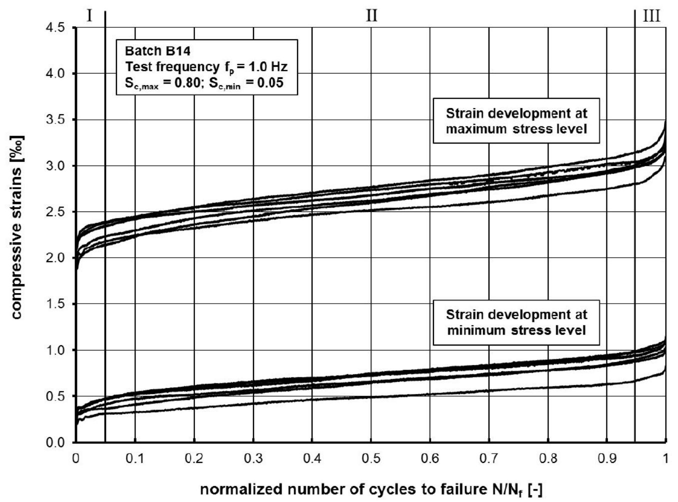


Figure 5: Three stage strain development [18]

Some variation of this curve is found as different stress levels and concrete types tend to change the ratio of the three stages. Using high strength concrete (HSC) as an example, a clear reduction in the first and third stage has been observed. This can be seen in Figure 6. For this type of concrete, stage 1 and 3 constitute about 5 % of the fatigue life[19]. As can be seen from Figure 6a, the transverse strains also follow the same three stage strain development as longitudinal, although mirrored across the abscissa (negative values).



(a) Longitudinal and transverse strain development of HSC[17]



(b) Longitudinal strain development of HSC[19]

Figure 6: Strain development for HSC due to cyclic loading

Further studies of the fatigue damage development have been performed using both ultrasonic pulse velocity technique and acoustic emission method. The ultrasonic pulse velocity method measures the time it takes the pulse to travel through a specimen, which will be influenced by internal cracking[20, p.632-633]. The acoustic emission method is based on crack formation as a consequence of energy release in the form of heat, vibration and the creation of new surfaces. The vibration part may be recorded using acoustic methods and thus form a picture of the damage development[14]. These two methods have shown the same three stage behaviour as the strain development[14, 21]. This can be seen in Figure 7.

Another characteristic behaviour of the fatigue process can be found by plotting the stress-strain curve for cyclic loading. This can be seen in Figure 8a. This hysteresis curve has received much attention due to its representation of the irreversible energy released by plastic deformation. The area of the hysteresis curve tends to decrease with increasing cycles, except at the end of its fatigue life where an increase of area is found. An example of the area evolution is shown in Figure 8b.

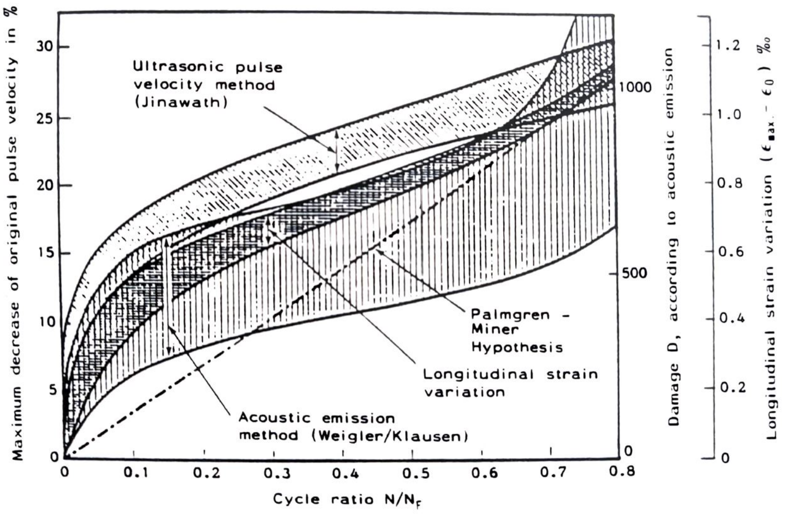
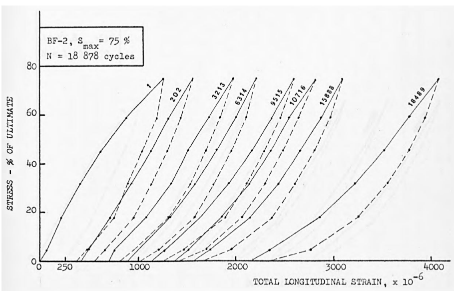
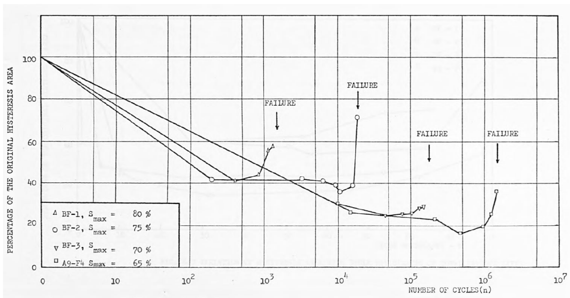


Figure 7: Different methods to measure fatigue degradation in concrete[21]



(a) Example of a typical stress-strain curve during cyclic loading[6]



(b) Change in area of hysteresis loop[6]

Figure 8: Strain development for HSC due to cyclic loading

The stiffness (E-modulus) of the specimen may be found as the tangent of the stress-strain curve. Following the change in stiffness from the stress-strain curve yields some insight into the three stage strain behaviour. This was done by Jinawath in his PhD thesis[6]. The first stage of the strain development corresponds well with the part of the stress-strain curve, where the loading branch goes concave towards the strain axis. This concaveness means a loss of stiffness during the loading branch. This behaviour is thought to be due to development of bond cracks between the matrix and the aggregate oriented parallel to the load, i.e. vertically for cylindrical specimens. This behaviour, both in stress-strain and decrease in pulse velocity, is not found in neat cement paste[22]. This supports the hypothesis of damage occurring at the matrix-aggregate interface. In the second stage of the strain development, the loading branches of the stress-strain curve straight out and eventually turn convex. This change is believed to occur due to existence of bond cracks perpendicular to the direction of loading and the closing of these, thus creating a stiffening effect during the loading branch. Despite this, the study of the secant elasticity modulus shows an overall decrease in stiffness during this second phase. The E-modulus does in fact also exhibit three stage behaviour as seen in Figure 9. The loss in overall stiffness could be explained by the widening of the existing vertical cracks while the horizontal cracks are closing. With the horizontal cracks closed, no further widening of vertical cracks seems to occur[6]. The third stage follows as the number of vertical cracks increase and the specimens fail.

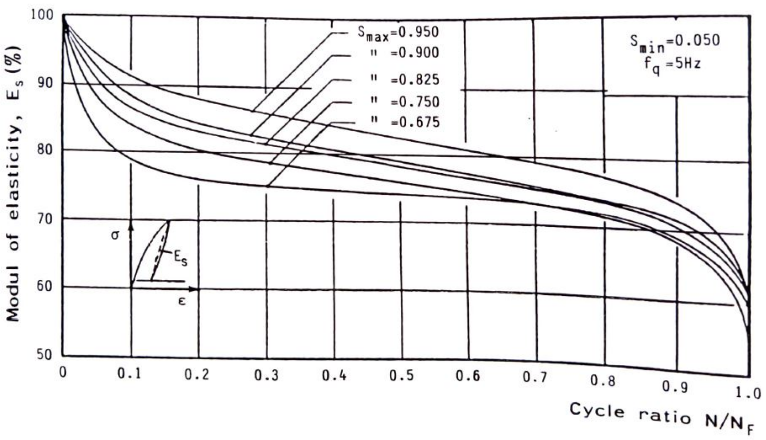
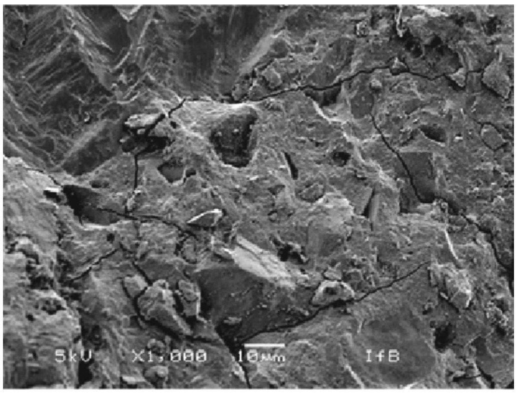


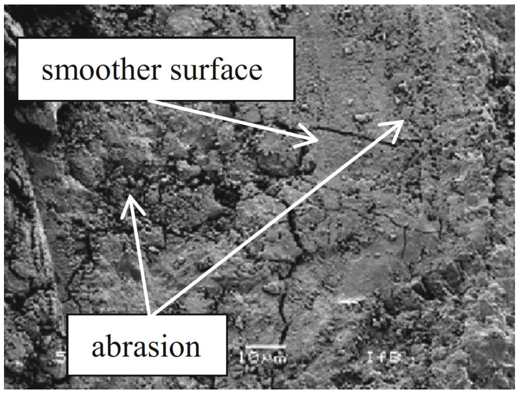
Figure 9: Change in secant elasticity module during fatigue loading[21]

2.2.1 Yielding Pattern

As mentioned, concrete does not seem to exhibit a clear fracture topography due to fatigue[12], at least not to the same extent as steel. In fact, concrete does not even exhibit such topography for monotonic loads. However, some general observations for different expected failure modes are found. Otto et al.[23] used a microscope and found that fracture surface of monotonic and fatigue loading exhibited certain differences. This is shown in Figure 10. The fracture surface of fatigue is significantly smoother than monotonic loading and some abrasion seems to occur. Obviously, discovering such differences is difficult with simply visual inspections, which are the basis of most investigations.



(a) Monotonic fracture



(b) Fatigue fracture

Figure 10: Fracture pattern due to monotonic and fatigue loading[23]

The yielding failure of plain concrete specimens loaded uniaxially tends to look similar the cubes shown in Figure 11 and 12. The main cracks go parallel to the direction of the loading[24], although it is typically some variation in the crack patterns. The main cracks resemble the failure mode of monotonic loading, however a larger amount of cracking tends to occur in fatigue. The location of the crack development in fatigue often occurs along the cement-aggregate interface[24], although variation is observed for different concrete types and qualities. Still, visual inspections seem to agree well with the hypothesis that fatigue is caused by microcracking occurring at the aggregate-cement paste interface.

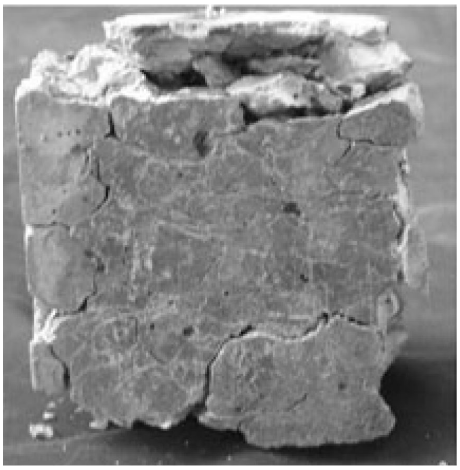


Figure 11: Failure mode of plain concrete cube due to uniaxially cyclic loading[25]

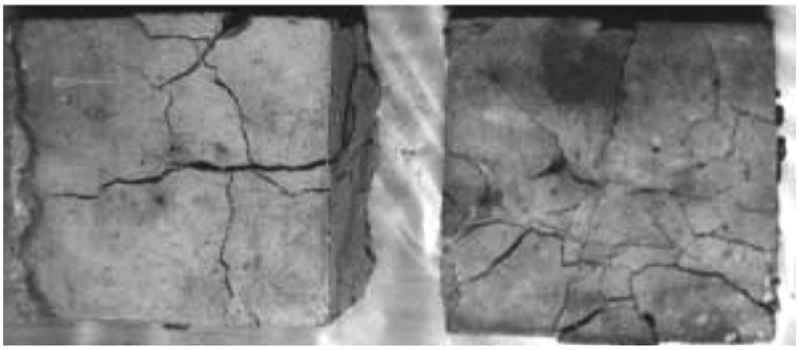


Figure 12: Failure mode of plain concrete cube due to uniaxially cyclic loading[24]

For monotonic loading, the microcrack formation mainly occurs along the aggregate-cement paste interface[20, p.302]. In addition, the formation and propagation of such microcracks have been registered to occur as low as 30% of the ultimate strength, and are highly dependent on the stress level[20, 26].

There are several reasons why one may expect the interface zone to be the location of microcrack formation. First, the different stiffness of cement and aggregate may cause extra stresses at this interface. This will be elaborated on in Section 3.2. There are also significant differences in the microstructure at this interface compared to the rest. This is partly due to a similar effect as the "wall effect"[20], where the cement is unable to be completely packed around the aggregates. Consequently, there is less cement to fill voids at this location during hydration. This causes formation of larger calcium hydroxide ($Ca(OH)_2$) in this zone [20, 27]. As a result, the transition zone has a higher porosity, which reduces the strength as seen in Figure 13[28].

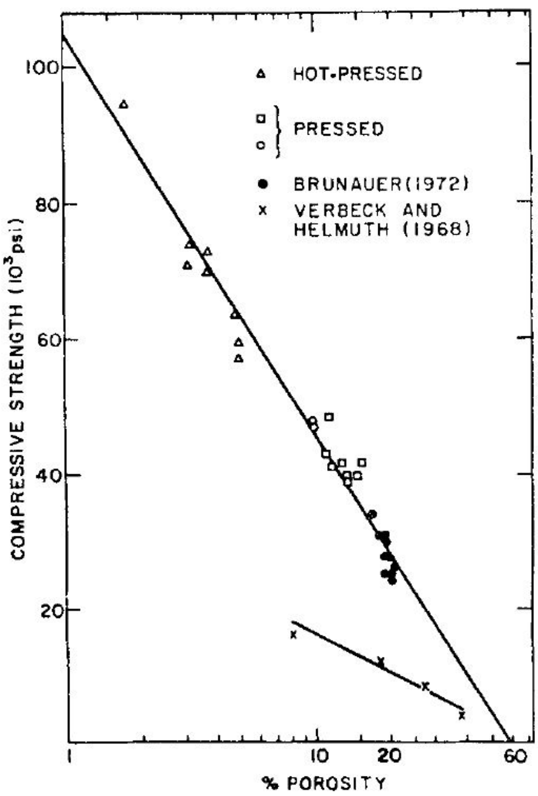


Figure 13: Effect of porosity on the compressive strength of cement paste[28]

Another reason for the decrease in strength of the interface zone is based on the constituents found in this area. The aggregate surface tends to be covered by a thin layer of $Ca(OH)_2$, approximately 0.5 μm, followed by a layer of 50 μm thick hydrated cement particles and larger $Ca(OH)_2$ crystals. This layer is without unhydrated cement[20, 27], indicating a higher water-cement (w/c) ratio than elsewhere in the mixture. In general, a higher w/c ratio results in weaker concrete strength[20, p.271-275]. The transition zone for concrete with lightweight aggregate (LWA) can potentially be without this weakness depending on the surface of the aggregate. If the aggregate has a dense outer layer, it will have the weakness as already explained. If it has a porous outer layer however, the transition zone will be denser and thereby improve the bond between aggregate and cement paste[20, p.303]. Taken together, there are many factors which can alter the formation and propagation of microcracks.

2.3 Remnant Static Strength

The yielding patterns of monotonic and cyclic loading are quite similar, despite more extensive crack formation in the latter case. This similarity makes it reasonable to assume that the consumption of the fatigue life with time is accompanied by a consumption of monotonic strength. This seems to be true for certain conditions, but there are cases where an increase in monotonic strength is found. How the fatigue life relates to the static life has been a subject often treated in investigations where some specimens do not fail within the expected time frame. These are treated as "runouts" and loaded monotonically to failure, to provide some insight into remnant strength. This means that each investigation is only based on a small number of specimens.

Petkovic[17] studied the relationship between fatigue and static life by reviewing the current knowledge as well as performing test of her own. Through her review, she found cyclic loading to have the following expected effects[17]:

- an increase in compressive strength in the direction of the cyclic load
- a decrease in the tensile strength in the direction perpendicular to the cyclic load
- a decrease in the tensile strength in the direction of the cyclic loading

Petkovic explained some of the mechanisms behind the expected results. The cyclic loading compacts and causes settlements within the concrete, which causes an increase in compressive strength[17]. The cracking occurring during cyclic loading is believed to be reason for the decrease in tensile strength, where horizontal and vertical cracking decreases the vertical and horizontal tensile strength, respectively. The experimental tests by Petkovic confirmed the expectations as shown in Figure 14.

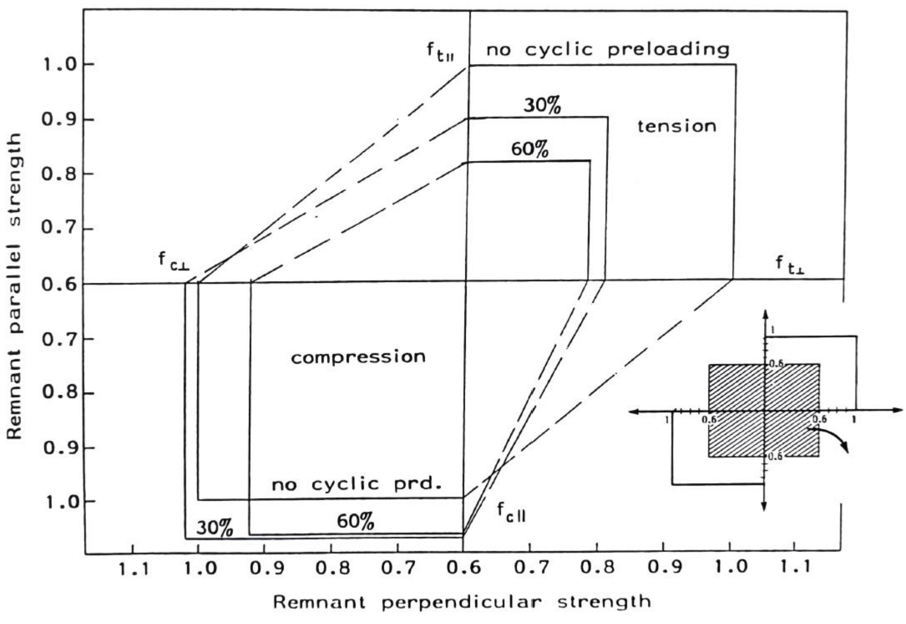


Figure 14: Results from investigation of remnant properties by Petkovic[17]

By loading to either 30% or 60% of expected fatigue life, an increase in compressive strength parallel to the load was found. However, the tensile strength was exclusively reduced. As Figure 14 shows, the increase in compressive strength is slightly less for the case with 60% than 30% consumed fatigue life, indicating a limit of the beneficial effect of cyclic preloading.

A recent investigation is in relatively good agreement with Petkovic. Isojeh et al.[29] studied the remnant strength of concrete and found an initial increase in compressive strength. As the fatigue life was consumed, the beneficial effect diminished and eventually became damaging. Some samples had a remnant static strength below 70% of the initial. Their results are shown in Figure 15. The results are somewhat chaotic, but correlate well with Petkovic where preloading is less beneficial when about half of the fatigue life is consumed.

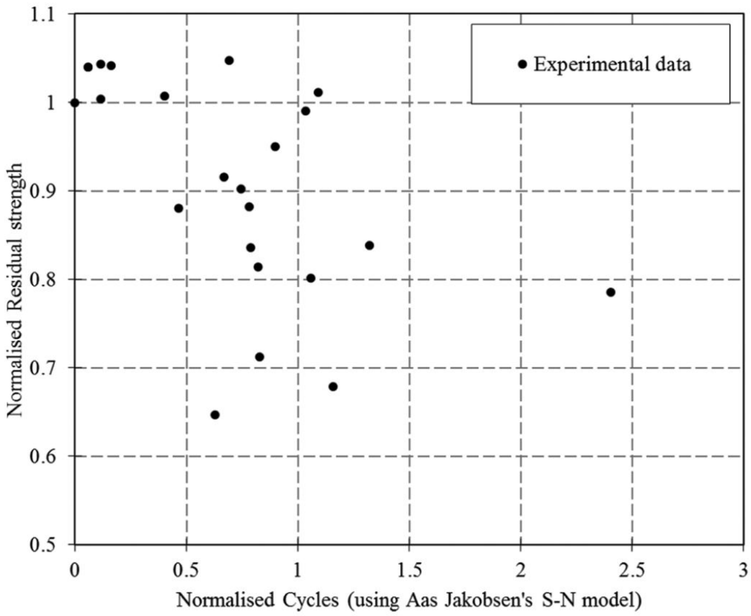


Figure 15: Remnant compressive strength compared to expected fatigue life according to Aas-Jacobsen's formula[29]

Fatigue tests tend to have a rather large amount of scatter, even more than monotonic. Hence, tests always deviate from the expected SN curves. A remedy for this was used by Isojeh et al.[29] where the strain gradient in the second phase (ε_{II}) of the strain evolution was used to estimate the fatigue capacity of the specimen. This method proved to be more reliable and offers a much better picture of how the remnant static strength is gradually degraded. This is shown in Figure 16.

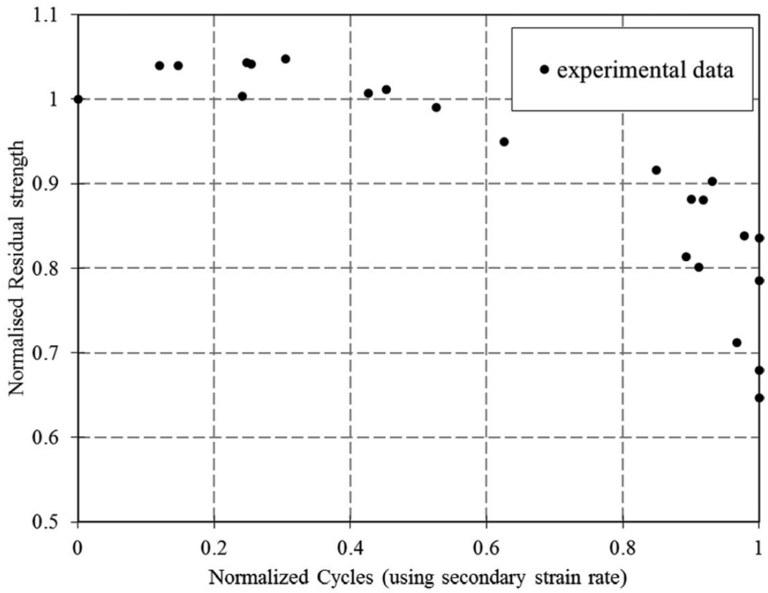


Figure 16: Remnant compressive strength compared to expected fatigue life according to strain approximation method[29]

Figure 16 shows that the beneficial effects seem to disappear completely at 50% of fatigue life consumption. Petkovic[17] indicated 60% consumption to be beneficial. This discrepancy might be partly caused by the fact that Petkovic investigated HSC while Isojeh et al. used NSC. Regardless, the trend is clear. Cyclic loading seems to initially increase compressive strength, but eventually the benefit disappears and may become harmful.

3 Factors Influencing Fatigue Capacity

Several studies have found different factors influencing the fatigue performance of concrete and these factors tend to interact. As a result, it is difficult to consider the factors as separate entities. Still, the following documentation of effects will take one factor at a time, despite this resulting in some repetition. For each factor, selected research will be presented in detail in order to explore and understand the effect at hand. To avoid tedious repetition of studies in agreement with previous described results, some are only mentioned shortly and sometimes only in the summarizing tables at the end of a section. These tables are also included in the appendices. The influence of each factor will be evaluated based on its ability to either change the endurable number of cycles for a given load setup (N_f) or its ability to withstand a higher maximum stress level (S_{max}) for the same amount of cycles.

3.1 Stress Level

Maximum stress level seems to have a larger influence on concrete than stress range, which stands in contrast to the observed effect on steel[30]. Most studies of concrete fatigue have utilized the SN-curves. Despite large scatter in fatigue testing, several researchers have found the logarithmic number of cycles at failure $log(N_F)$ to be approximately normally distributed at each stress level [6, 21]. Furthermore, a linear relation between maximum stress level and the logarithmic number of cycles is generally assumed as discussed in Section 2.1. Several of empirical formulas have been generated using this sort of linear relation to approximate fatigue life of plain concrete, a selection is shown in Figure 17.

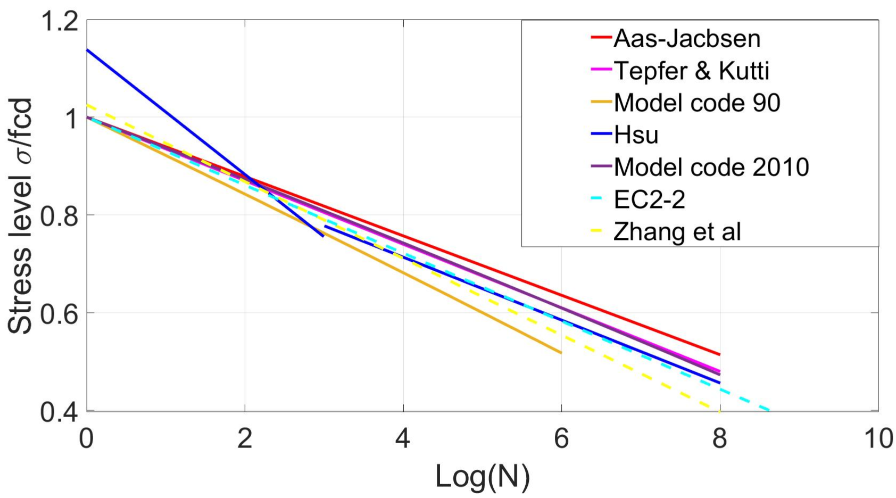
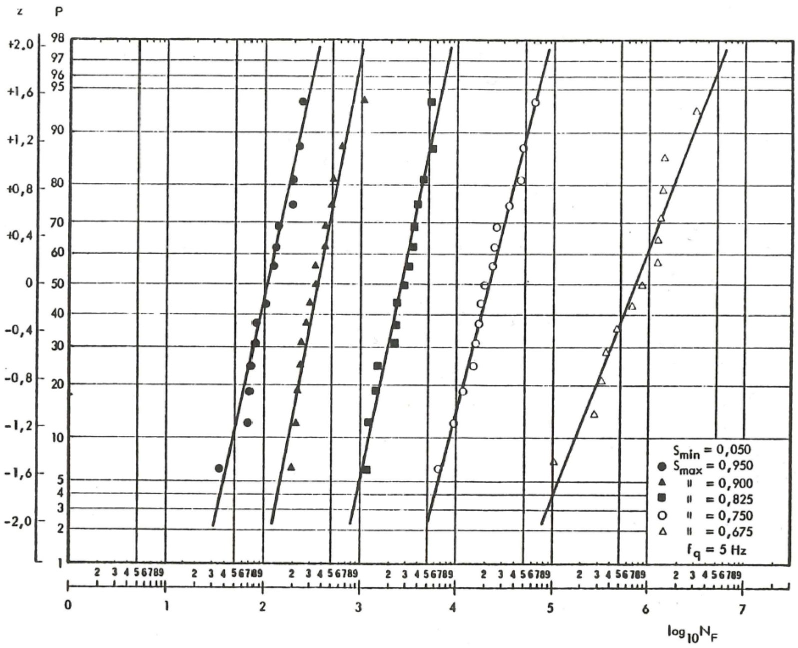
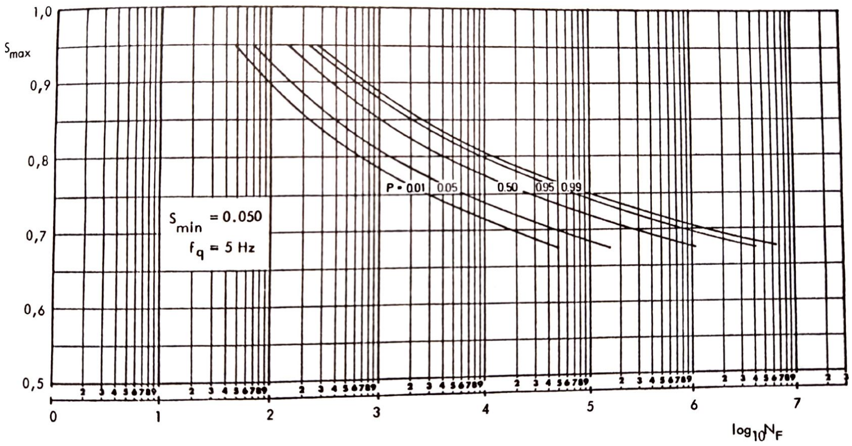


Figure 17: Regression formulas for concrete fatigue from various references [11, 31–36]

This linear relation is an approximation with varying level of accuracy. Holmen[21] studied the linear assumption by plotting the cumulative frequency distribution for the fatigue life at different maximum stress levels, as can be seen in Figure 18a. It was noticed that an approximately logarithmic normal distribution fitted well at each stress level. However, the standard deviation of the amount of cycles increased with decreasing stress level[21]. This suggests that the assumption of a linear relation between S_{max} and Log N is slightly incorrect. Holmen proposed a new curve with better fit as shown in Figure 18b.



(a) Cumulative frequency distribution of fatigue life



(b) SN-curve proposed by Holmen

Figure 18: Investigation of the SN relation by Holmen[21]

Despite the inaccuracy in S_{max} to Log N relation, it has remained common to approximate the SN-relationship as a linear relationship. It is also common to distinguish between High and Low cycle fatigue as mentioned in Section 2. The need to distinguish between these two categories is based on different observed behaviour of concrete for High and Low cycle fatigue. The formulas based on higher cycles represent a rather poor fit for the behaviour of lower cycles. One of the few formulas to account for low cycle behaviour is made by Hsu[11], and is shown in Figure 17. It is noteworthy that this formula also accounts for frequency of load and sustained loading effects. As a result, the curve might intersect with the ordinate above one (as in Figure 17) or below one depending on input parameters. This highlights another shortcoming of the conventional SN curves. The limit at one for zero cycles is merely a set limit and does not necessarily reflect real conditions[19]. This start restriction of the SN curves also influences the regression lines making them slightly more inaccurate.

A summary of studies concerning the stress level in relation to fatigue is shown in Table 1.

Table 1: Investigations of the effect of stress level with respect to fatigue

Author	**Noticed effect**	**Notes**	**Year/ Source**
Aas-Jacobsen	S_{max} has a linear relation to Log N	Formulated the famous Aas-Jacobsen formula	1970[37]
Jinawath	S_{max} has a linear relation to Log N		1974[6]
Holmen	Nonlinear relation between S_{max} and Log N		1979[21]
Hsu	Established separate regression lines for low and high cycle fatigue	Considered several factor	1981[11]
Lenschow	Concrete fatigue is mainly influenced by S_{max}		1982[30]

3.2 Composition of Concrete

The strength of concrete is highly influenced by its composition, and the composition also influences the failure mechanism [20, p.271-310]. The question of interest for this thesis is to which extent the composition influences fatigue, and if it shows any additional influence besides the known effect on static strength.

Some literature suggest that the composition of NSC influences the fatigue equally to the static case. As most fatigue strengths are presented as a ratio of the static strength, the influence of composition is not registered[14]. However, more recent research suggests that concrete composition may be of great importance to fatigue properties even when referred to as a ratio of static strength. Breitenbücher et al.[38] investigated this topic in 2008 and performed tests on NSC with three different types of aggregate: basalt, quarts and sandstone. The three different concrete compositions were similar in all ways but the coarse aggregate and achieved the same strength classified as C30/37. The tests studied the difference in microcracking and strain development. Hence, no comparison of the total amount of withstanding cycles is given. On the other hand, the paper[38] thoroughly explains the formation of microcracks at different number of cycles, and a clear trend is observed. The stiffer aggregates basalt and quarts, with E-modules at approximately 90 GPa and 60 GPa, experience severe cracking. Sandstone with E-modulus between 20 to 50 GPa, showed less severe cracking. This can be seen from Figure 19, where the expansion of crack width is shown for the three concrete compositions.

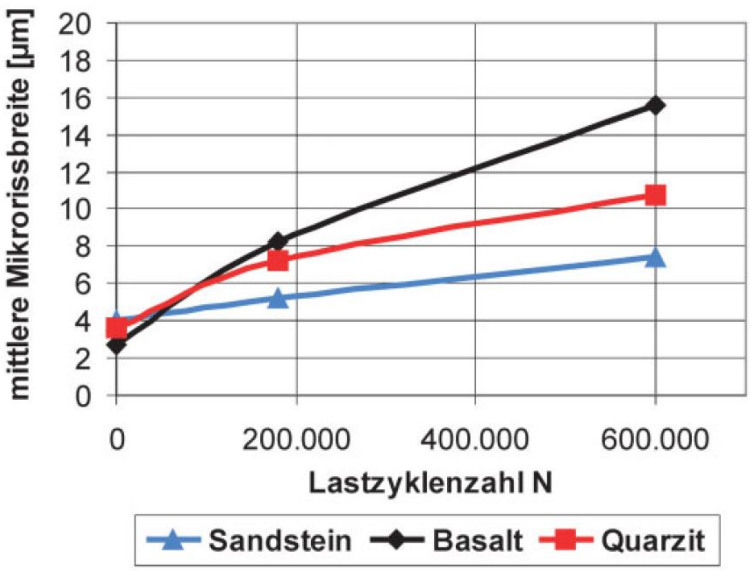


Figure 19: Crack width development in different concrete compositions by Breitenbücher et al. [38]

It should be noted that sandstone is much closer to the stiffness of the cement paste ($\approx 20GPa$), thus creating a more uniform stiffness throughout the specimen. This is believed to be the reason for less crack growth under cyclic load for sandstone than the others compositions. According to the Breitenbücher et al.[38] this shows that the degradation due to fatigue is larger for compositions with large difference in the stiffness of aggregate and cement paste[38]. This result is of great importance since it substantiates the major hypothesis for fatigue damage, namely that the interface between cement paste and aggregates is the origin of the fatigue damage.

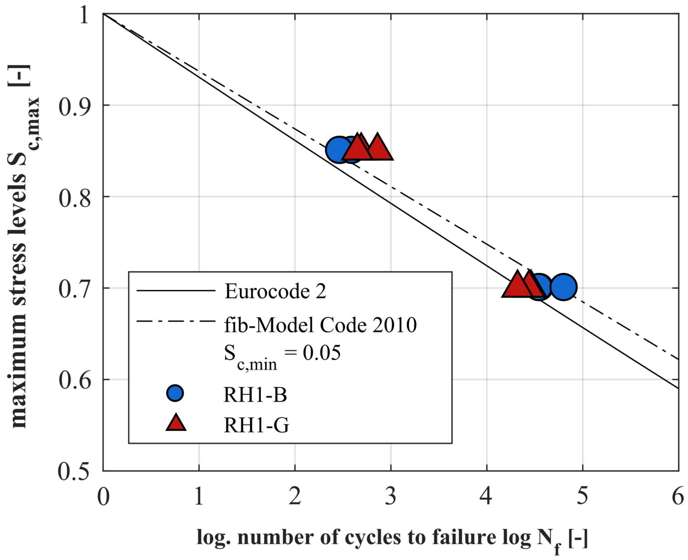


Figure 20: Cycles to failure compared to Eurocode and Model Code 2010 [39]

In 2019 Scheiden and Oneschkow[39] published a paper concerning the effect of aggregate type and fatigue properties on HSC. They studied two types of concrete compositions, one with basalt aggregate and another with granite. Both compositions had the same particle size distribution and a maximum aggregate size of 8 mm. The concrete strengths of the basalt and the granite compositions were 113 and 109 MPa, respectively. This small difference was considered negligible by Scheiden and Oneschkow[39]. The loads were pure compression sinusoidal 1 Hz loads with two different maximum stress levels of 0.85 and 0.7. The fatigue behaviour of the concrete was as expected from the empirical curves given in both the Eurocode[40] and the Model Code 2010[34]. This can be seen in Figure 20. One noticeably effect is the change in the "strongest" concrete composition. For $S_{max} = 0.7$, basalt composition (RH1-B) is the strongest. At the higher level, they switch and granite becomes strongest. The exact explanation for this effect is unknown. However, Scheiden and Oneschkow[39] analysed the strains and acoustical emissions from the samples and noticed a clear change in material behaviour at the different stress levels. This indicates that the aggregate composition may change the damage mechanism. The acoustical emissions showed a clear difference for the two compositions, as can be seen from Figure 21. The scaling of the two plots is quite different and the acoustical emissions of granite with S_{max}=0.7 completely surpass those of basalt. This large difference is assumed to be caused by the presence of many, although smaller, amplitude acoustical emmissions, i.e. fainter cracking sounds, for granite at S_{max}=0.7 than basalt. Interestingly, the expected three stage behaviour is not found in the acoustical emission diagram for the granite at S_{max}=0.7. The lack of this behaviour recurred in all the tested specimens. Scheiden and Oneschkow did not provide an explanation for this discrepancy since further investigations were needed. Despite the lack of the three stage behaviour from the acoustical emission measurements, the strain development did exhibit this three stage behaviour for both samples at all stress levels.

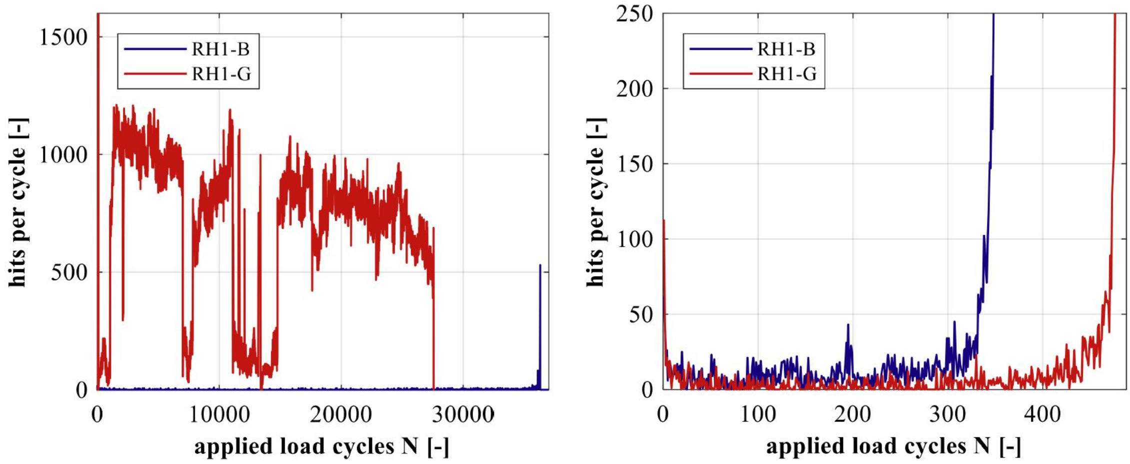


Figure 21: Acoustical emissions for two concrete compositions, granite (RH1-G) and basalt (Rh1-B) for two different maximum stress levels, S_{max}=0.7 (left) and S_{max}=0.85 (right)[39]

As described in Section 2.2, the strains and acoustical emissions are used as a damage indicators since plastic strains may dissipate the energy from cyclic loading. The reason for this dissipative effect of plastic deformation is thought to be due to plastic sliding along the aggregate interfaces[41]. However, additional dissipative mechanisms might occur in HSC due to cracking through the aggregate[41]. This might explain some of the differences in behaviour of NSC and HSC. This assumption however, lacks experimental verification according to Baktheer and Chudoba[41]. On the other hand, Håverstad and Jensen[42] published a state-of-the-art report on HSC with LWA in 1986. They found that the crack propagated through the aggregate for such samples. This does to some extent verify the assumption of additional dissipating mechanisms for HSC.

Clearly, the effect of composition on fatigue capacity can not be completely neglected, even when fatigue strength is measured as a ratio of static strength. A summary of selected findings of this topic is given in Table 2.

Table 2: Studies of the effect of concrete composition with respect to fatigue

Author	**Studied composition**	**Noticed effect**	**Notes**	**Year/ Source**
Murdock	Light weight aggregate	No significant variation in fatigue life of lightweight aggregate compared to NSC when stress level is expressed as a ratio of to static strength		1965[43]
RILEM Comittee 36-RDL	Composition as a whole	Influences fatigue strength in similar manner as static strength and therefore not noticeable when fatigue strength is given as a ratio of static strength		1984[14]
Håverstad and Jensen	HSC with lightweight aggregate	Crack propagation through the aggregate itself		1986[42]
Petkovic	HSC vs NSC	Fatigue life related to static strength shows little difference between HSC and NSC, however the deformation behaviour changes noticeably	The observations is in agreement with Breitenbucher et al.[38] where a more uniform stiffness results in less stiffness degradation	1991[17]
Breitenbücher et al.	Coarse aggregate	Coarse aggregate with similar stiffness as the cement paste yields less microcrack growth and thereby less degradation per cycle		2008[38]
Scheiden and Oneschkow	Coarse aggregate	Indications that change in aggregate type yields different damage mechanism		2019[39]

3.3 Loading Rate and Frequency

The effect of frequency on fatigue performance has been the subject of many studies with various conclusions. Some investigations discovered small to none influence of frequency, while other found large influence. The major findings from some of these studies are presented below, and a summary is provided in Table 3.

Several studies have found frequency to be irrelevant for fatigue performance. Arthur et al.[44] exposed concrete beams to frequencies(f_q) from 0.17 to 5 Hz, with no noticeable effect on fatigue life. This result corresponds well with the results obtained by Murdock[43], which indicated that frequencies in the interval 1.16-15 Hz have little influence on fatigue life given a stress level below 75% of static strength. Raithby and Galloway [45] were also unable to find any frequency effect on fully saturated beams when comparing a sinusiodial load of 4 Hz with 20 Hz. Significantly higher frequencies were investigated by Assimacopoulos et al. [46] for $S_{max} < 0.75$, without any noticeable frequency effect. However, the number of specimens was limited and Assimacopoulos et al. emphasized the need of further tests in order to gain more reliable results.

At levels above 75% of static strength, Awad and Hilsdorf[47] found the frequency to be an important parameter, where decreasing load rate resulted in a reduced fatigue strength. This conclusion is also supported by tests performed by Sparks and Menzies [48], and later by Holmen[21], Zhang et al.[36], Oneschkow[19] and Isojeh et al.[29]. At $S_{max} > 0.75$, most specimens fail before 10^3 cycles. This means that they belong to the Low cycle fatigue domain.

In contrast to the most common approach where frequency is considered against cycles before failure, Oneschkow[19] focused mainly on strain evolution and how frequency influences this. The objective of this approach was to gain further insight into the damage development. Her results indicated, in addition to a noticeable reduction in strength with reducing rate, a changed behaviour of strain development as a result of altered frequency. This analysis was based on the gradient of the strain development in stage two, that is approximately from 20% to 80% of the fatigue life, denoted as the secondary strain gradient (ε_{II}).

The frequency seems to have the opposite effect as changing the maximum stress level. This is seen in Figure 22. A higher stress level increases the strain gradient. This is expected as it leads to a faster damage progression per cycle. In contrast, a higher frequency yields a smaller strain gradient. This is expected since the fatigue life tends to increase in such cases. The influence of frequency on the number of cycles is perhaps better illustrated by the results from Isojeh et al.[29] as seen in Figure 23. Note that the SN curve is not semilogarithmic, and therefore lacks the customary linear shape.

Although frequency has been the parameter of primary interest in fatigue testing, some of the effects attributed to the frequency may be caused by the difference in static and cyclic loading rate. The loading rate is the rate at which force is applied to the specimen. This variable is directly related to static strength determination. The loading rate is known to influence strength, which is why the Eurocode specifies a

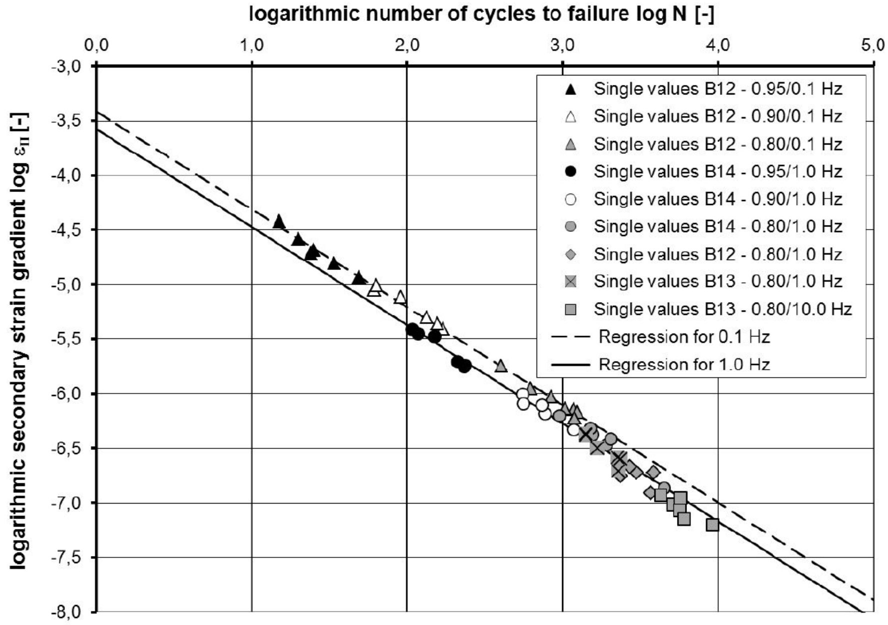


Figure 22: Logarithmic secondary strain gradient for different frequencies and stress levels [19]

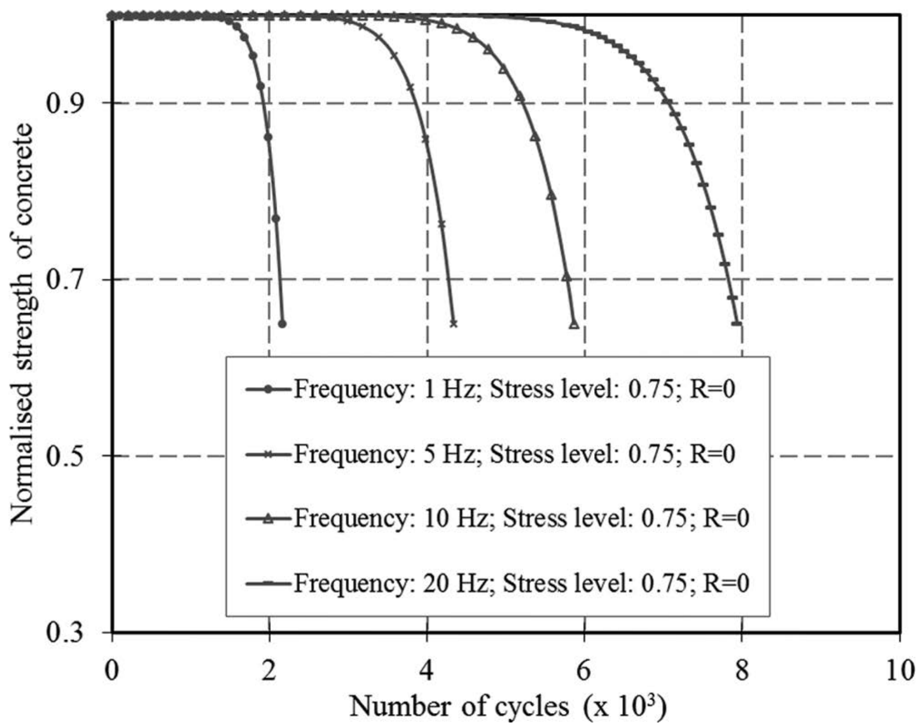


Figure 23: Effect of frequency on the fatigue capacity[29]

loading rate of 0.6 $\pm$2 MPa/s when applying the load for testing of static strength[49]. A unified loading rate is needed when testing the static capacity in order for different static capacities to be comparable. The effect of loading rate on the static strength has been reported by several studies and increased loading rate is known to increase the static strength[48, 50, 51].

Every fatigue test will include a certain loading rate, but most studies focus on the load frequencies and stress levels which together make up the components of the loading rate. However, by focusing on these two parameters and not the actual loading rate, most tests will include a wide range of loading rates. This makes the comparison of the effect on static and cyclic strength rather troublesome. Some studies have investigated the loading rate specifically. Sparks[52] published a paper on this in 1982, testing the effect of loading rate on both the static and fatigue strength. He concluded that an increase in fatigue strength resulted from an increase in loading rate, but no rate effect could be observed when the static strength was compared to the fatigue strength at the same loading rate [52]. This suggests that the change of strength in fatigue is equal to the change in static strength, even though the rate of loading might influence the fatigue strength.

Taken together, the frequency and loading rate influence the fatigue capacity, and should be considered as long as the reference strength is set at a constant loading rate. A summary of investigations into this topic is given in Table 3.

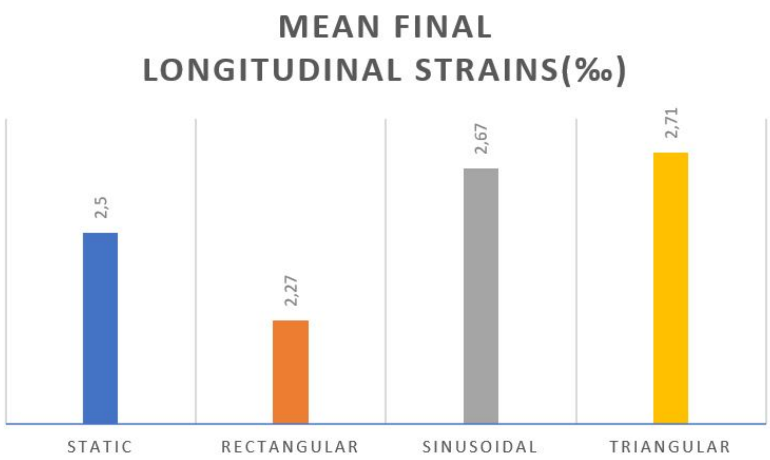
Table 3: Investigations of loading rate and frequency with respect to fatigue

Author	Frequencies studied [Hz]	Noticed effect	Notes	Year/ Source
Assimacopoulos et al.	8.33 & 150	No consistent difference	$0.60 < S_{max} < 0.95$ & small number of specimens	1959[46]
Murdock	1.16 - 5	No effect		1965[43]
Awad & Hilsdorf	Various	Decreasing f_q leads to decreased fatigue life	$S_{max} = 0.9$	1971[47]
Sparks & Menzies	Various	Decreasing f_q leads to decreased fatigue life	$S_{max} > 0.7$	1973[48]
Raithby & Galloway	4 - 20	Negligible effect	$S_{max} < 0.75$	1974[45]
Holmen	1, 5 & 10	Decreasing f_q leads to decreased fatigue life	$S_{max} > 0.75$	1979[21]
P. D. Arthur et al.	0.17 - 5	No effect		1982[44]
Sparks	Various	No effect if the cyclic loading rate is compared to the static capacity at equivalent loading rate	Continuation of work by Sparks and Menzies[48]	1982[52]
Zhang et al.	10^{-3} - 30	Decreasing f_q leads to decreased fatigue life	$S_{max} > 0.8$	1996[36]
Oneschkow	0.1, 1 & 10	Decreasing f_q leads to decreased fatigue life	$S_{max} > 0.80$ & HSC	2012[19]
Hümme et al.	1 & 10	No clear influence of frequency	$S_{max} = 0.80$ & 0.6 & NSC	2016[53]
Isojeh et al.	1,5,10,20	Decreasing f_q decreases fatigue capacity		2017[29]

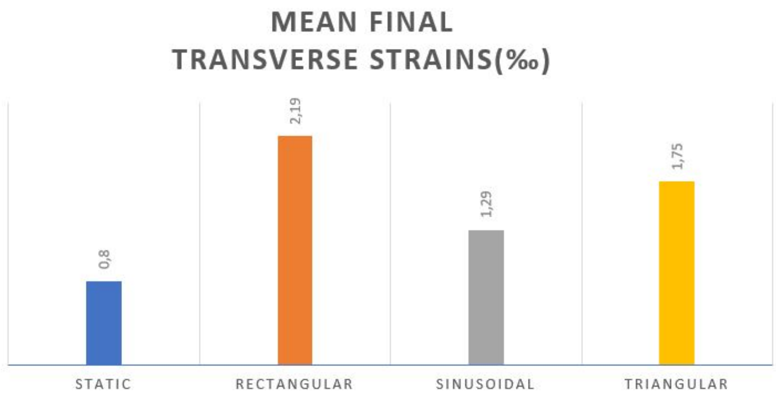
3.4 Loading Waveform

Waveform is closely related to the loading rate and frequency. Different waveforms yield different ranges of loading rate for each given frequency. Treating them as one variable might be problematic, and this assumption lacks scientific evidence.

Tepfers[54] published a paper concerning different waveforms where he presented the results from an investigation by Görlin and Samuelsson. Three different waveforms (rectangular, sinusoidal and triangular) were studied. Their test specimens were concrete prisms loaded in compression. The rectangular waveform was found to be more damaging than the others, causing more deformation for a certain number of cycles and induced failure after fewer cycles. However, the triangular load yielded the largest strains for a given cycle ratio (N_i/N_f) as well as the largest final strains. Furthermore, the total amount of cycles was also highest for the triangular load. A comparison of the failure strain at the mean stress level for the cyclic loads, $S_m = 0.45$, and the failure strains from monotonic load is given in Figure 24.



(a)



(b)

Figure 24: Failure strains for various wave forms, from data given by Tepfers[54]

Another investigation of the effect of different waveforms was performed by Oneschkow[18] who tested sinusoidal and triangular waveforms. Her findings are in agreement with Tepfers[54]. The triangular load seems to cause less damage per cycle and thus those specimens endured most cycles. Furthermore, the strain growth due to triangular load is higher than the sinusoidal load. As seen in Figure 25, the difference is considerable. Using the level where $S_{max} = 0.8$ as an example, the sinusoidal load has a mean value of approximately 700 cycles while the triangular loads have a mean value of approximately 2700 cycles. The triangular load seems to increase the number of cycles more than three times compared to sinusoidal load. This increase is larger than the tests presented by Tepfers[54], where an increase of about 1.8 times the number of cycles was found for triangular loading. Both studies are in agreement concerning the effect of different waveforms, and the waveform of the loading influences the fatigue capacity. Table 4 summarizes the main findings from the two studies.

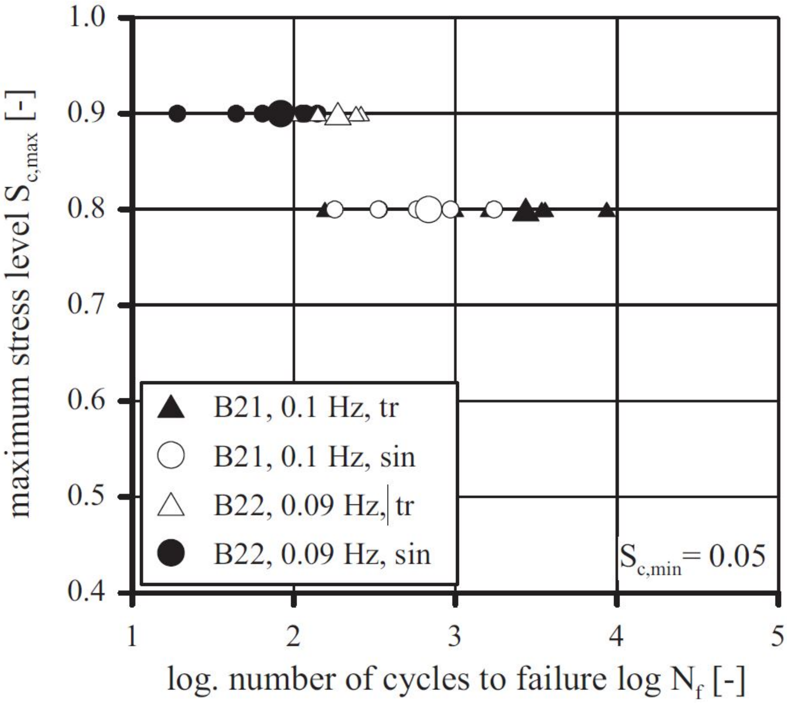


Figure 25: Difference in fatigue capacity for specimens exposed to different waveforms[18]

Table 4: Investigations of waveforms with respect to fatigue

Author	**Waveforms studied**	**Noticed effect**	**Notes**	**Year/ Source**
Tepfers et al.	Rectangular, triangular & sinusoidal	Waveform influences both fatigue capacity and strains		1973[54]
Oneschkow	Triangular & sinusoidal	Waveform influences both fatigue capacity and strains		2016[18]

3.5 Moisture

Water is one of the most fundamental components of concrete and concrete will therefore always contain a natural water content. The study of concrete strength has found a well-established relation between the ratio of water and cement (w/c) and their effect on static strength. This is shown in Figure 26.

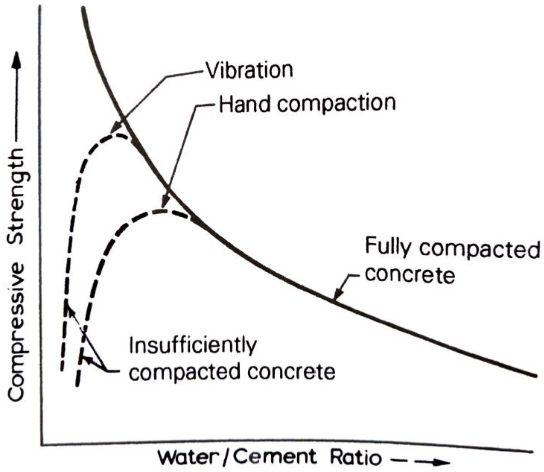


Figure 26: Relation between strength and w/c ratio[20]

Investigations of moisture and fatigue have attempted to assess if both natural moisture content and external moisture/water influence the specimens beyond their effects on static strength. Galloway and Raithby[45] studied this in 1973. Their investigation concerned the effect of moisture on plain concrete beams exposed to bending. Therefore, the modulus of rupture was the parameter of interest. They used a concrete mix with w/c ratio equal to 0.5. All specimens were initially cured in water at 20°C until they were implemented in the test regime. Four moisture states were tested as shown in Table 5. The results are shown in Figure 27. Galloway and Raithby found dry samples to endure most cycles. Interestingly, they also found the moisture gradient to be of greater importance than the moisture amount itself.

Moisture states	Description of state
1	Specimens saturated throughout testing
2	Specimens allowed to dry at 20°C and 65% RH for one week
3	Specimens oven-dried at 105°C for one week
4	Specimens oven-dried at 105°C for one week then resoaked for 3 weeks

Table 5: Moisture states by Galloway and Raithby[45]

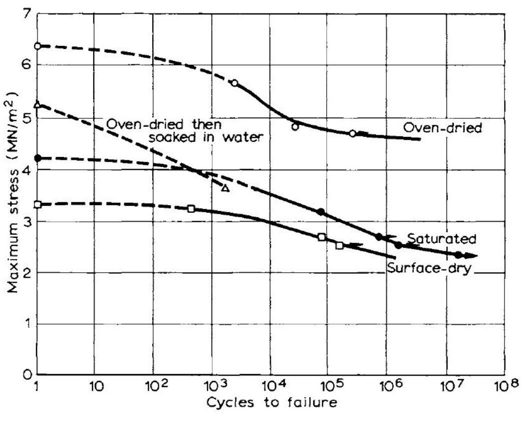


Figure 27: Moisture influence on fatigue by Galloway and Raithby[45]

Corneliussen and Reinhardt[55] conducted tests on dry and sealed cylindrical specimens in 1984. The concrete mix had a w/c ratio equal to 0.5 and the specimens were exposed to sinusoidal pure tension/tension-compression loads at 6 Hz. Despite a large scatter in their results, sealed specimens generally failed faster than dry ones when exposed to pure tension[55]. The tests with stress reversal (tension-compression) showed no clear difference for the two moisture states.

Petkovic[17] performed tests on the effect of moisture in cylindrical specimens exposed to constant amplitude sinusoidal cyclic compression loading. The maximum stress level was set to 70% of the static strength, with a frequency of 1 Hz for the two smallest specimens and 0.5 Hz for the largest. The effect of the frequency difference was assumed to be negligible, which corresponds well with the frequency effect documented in Section 3.3. The tests included three sizes of cylinders (Ø50, Ø100 & Ø450) and three different moisture conditions (air, sealed & water). The w/c ratio of the concrete mixes were 0.5, 0.36 and 0.4 for ND65, ND95 and LWA75, respectively. Three different sizes were included to investigate if the effect of moisture was a surface phenomenon as earlier investigations had indicated. This means that the evaporation of water occurs only at the outer layers of the concrete, i.e. concrete close to the surface dries out. Consequently, larger specimens inhibit the moisture evaporation from its core and yield a state similar to a sealed state. The results of this investigations can be seen from Figure 28.

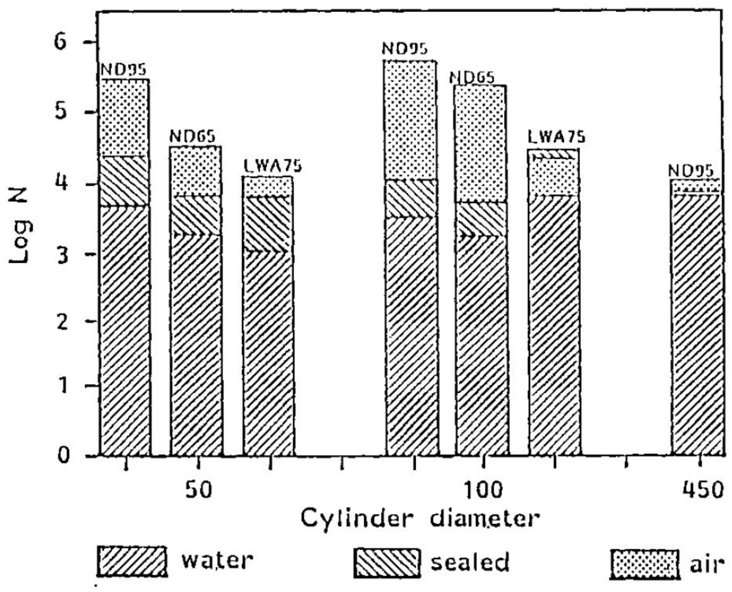


Figure 28: Results of the moisture investigation from Petkovic et al.[56]

Petkovic[17] drew the following conclusions from the tests:

1. Sealed specimens are least scale dependent
2. Excessive water content decreases fatigue life, while water drying extends it
3. Large indications that moisture effects are a surface phenomenon, thus scale dependent

To truly substantiate that the moisture effect is a surface phenomenon, the results should have shown the smallest specimen to exhibit the largest variation in strength. However, this was not the case. The deviation was believed to be caused by a small aggregate to cylinder ratio and large relative damage resulting from drilling the sample. The behaviour of the sealed specimens was in general much closer to the water samples than the air samples in terms of fatigue capacity. This indicates that the natural water content of concrete is sufficient to cause a reduction of fatigue strength.

Tomann and Oneschkow[57] conducted a more recent study, and also found the natural water in the microstructure to be the major contributor to strength reduction. External water contribution was minor in comparison. Tomann and Oneschkow exposed cylindrical specimens to a sinusoidal compression loading at 1 Hz, with an S_{max} and lower stress limit (S_{min}) of 0.65 and 0.05, respectively. The specimens were stored under several different conditions to create the following five moisture states:

1. Dried (D)
2. Climate chamber stored; 20°C, 65% RH (C)
3. Sealed (M)
4. Water stored but tested in air (WS)
5. Water stored and tested (WST)

Under normal conditions (moisture state 2) the HSC shows fatigue strength which corresponds well with FIB Model Code 2010[34]. This is seen in Figure 29. Furthermore, the effect of moisture becomes clear when comparing the dry specimen with the others. The dry specimen was exposed to almost 10^7 cycles without failing, while specimens with free moisture in the microstructure fractured well below 10^6 cycles.

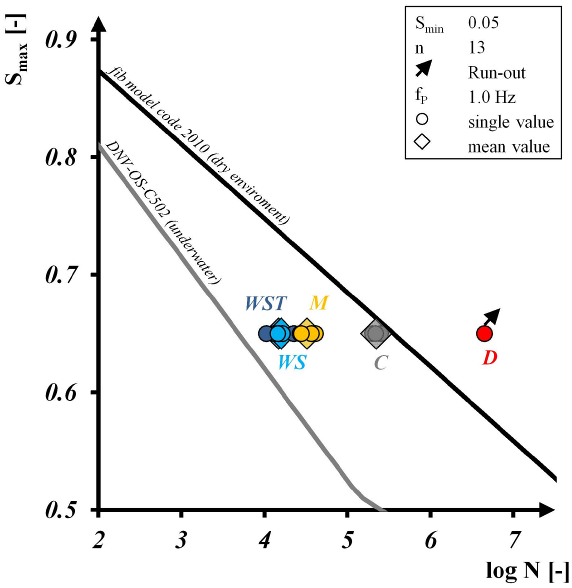


Figure 29: Results of the moisture investigation from Tomann and Oneschkow[57]

In addition, the tests by Tomann and Oneschkow[57] showed a clear indication of increase in the elasticity modulus with increased moisture content. The increase in the elasticity modulus translates to an increase in stiffness of the specimen. Despite this increase, the yield strength of the specimens showed very little increase. A possible explanation is adopted from Hümme[58] and Sørensen et al.[59], where it is suggested that an increase in water content leads to pore-water pressure which adds tensile stresses in the microstructure. Additionally, the effect of water-pumping between pores during cyclic loading may results in further degradation.

To substantiate the hypothesized damage effects, Tomann and Oneschkow[57] recorded acoustic emission during testing. As can be seen from Figure 30, the specimens with higher levels of moisture experience more acoustical emissions per cycle. This indicates a more progressive deterioration as a result of moisture. Further investigations showed that the high moisture specimens had large emissions around the minimum stress levels[57]. This is opposite from the dry specimens where sound is emitted mostly at high stress levels. Hence, it indicates different damage mechanisms due to moisture. In conclusion, the state of moisture is an important parameter for fatigue capacity as shown by the summary of studies in Table 6.

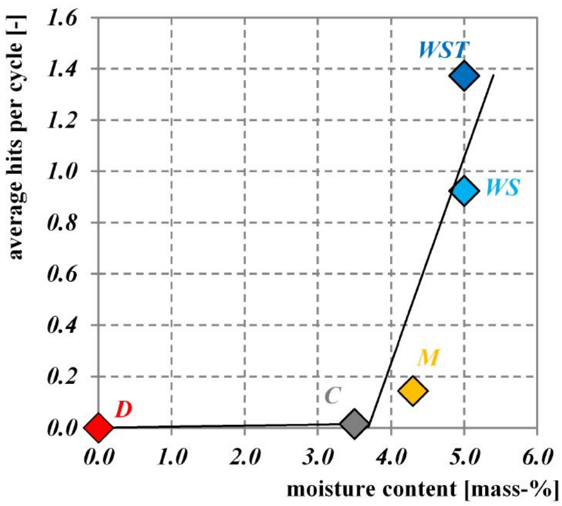


Figure 30: Acoustic emission activity according to Tomann et al. [57, 60]

Table 6: Investigations of moisture content with respect to fatigue

Author	**Moisture conditions**	**Noticed effect**	**Notes**	**Year/ Source**
Galloway and Raithby	Dry, partly dry and wet	Moisture reduces fatigue life and moisture gradients increase damage	Bending of pure concrete beams	1974[45]
Cornelissen and Reinhardt	Dry and wet	Increased water content reduces fatigue life	Centric tension	1984[55]
Håverstad and Jensen	Dry and wet	Specimens in water had 1/3 of the fatigue life compared to samples in air	HSC with LWA	1986[42]
Petkovic	Dry, sealed and wet	Increased water content reduces fatigue life, and even a natural water content may be damaging	Centric compression	1990[17]
Tomann and Oneschkow	Dry, semi-dry, sealed, wet and submerged	Natural water content causes reduction in fatigue life to a larger extent than external water	Centric compression	2019[57]

3.6 Rest Periods

The study of strength recovery inbetween cyclic loading has received little attention, and the knowledge is therefore somewhat limited. Despite this, the few studies on this subject have found some noteworthy tendencies.

In 1966, Hilsdorf and Kesler [61] investigated the effect of rest periods inbetween cyclic loading on plain concrete beams. The loading program is shown in Figure 31 and consisted of 4500 load cycles before resting period, where the resting duration was either 1, 5, 10, 20 or 27 minutes. The upper stress level ranged from 0.69 to 0.75, with a constant stress level ratio of R=0.17.

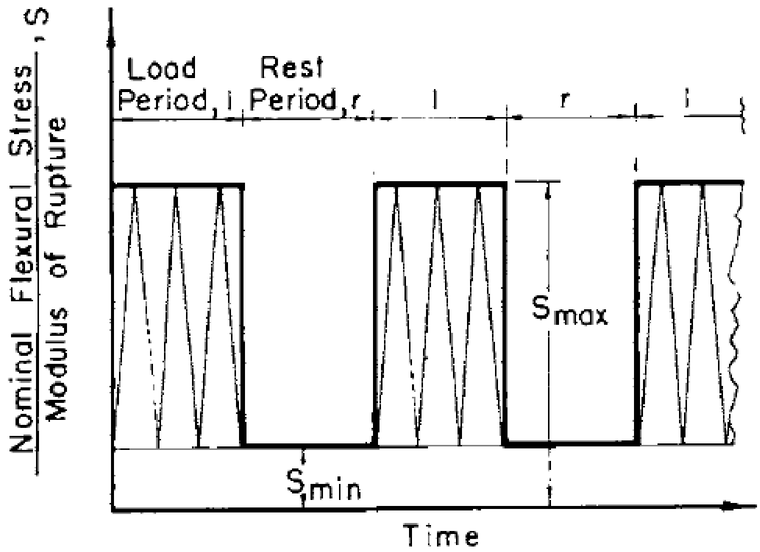


Figure 31: Rest period program by Hilsdorf and Kesler[61]

Hilsdorf and Kesler[61] identified a positive effect of rest periods on fatigue strength up to 5 minutes. A rest period above 5 minutes gave no extra contribution. Every resting period resulted in an increased fatigue strength compared to continuous loading, which is also visible through the regression lines in Figure 32. The increase however, appears to be rather small and only relevant for high number of cycles.

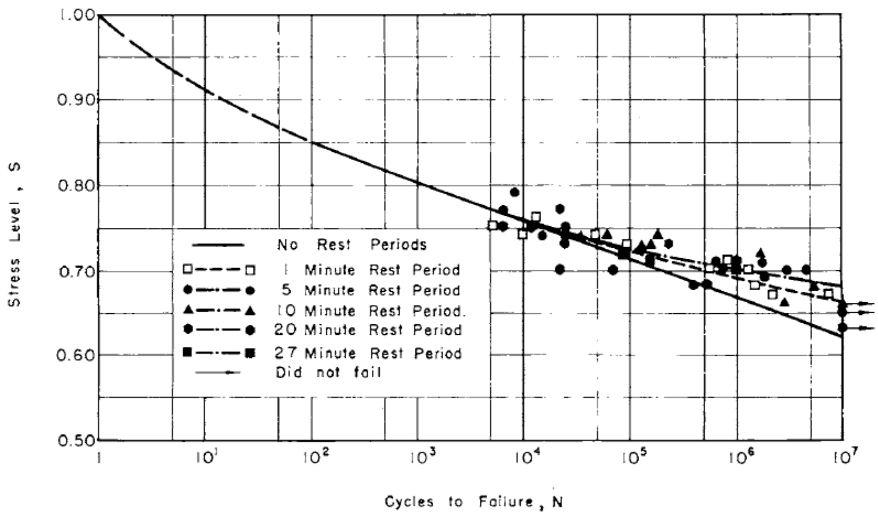


Figure 32: SN-curve for results from Hilsdorf and Kesler[61]

Hilsdorf and Kesler[61] conducted an additional statistical analysis to determine the effect of rest periods. The method they used was adopted from an article by McCal [62]. The results of the analysis from Hilsdorf and Kesler [61] are shown in Figure 33, where the probability of failure is shown for different upper stress levels, denoted S in the figure. When presented in this form, the resting periods clearly show an increasing effect on fatigue strength.

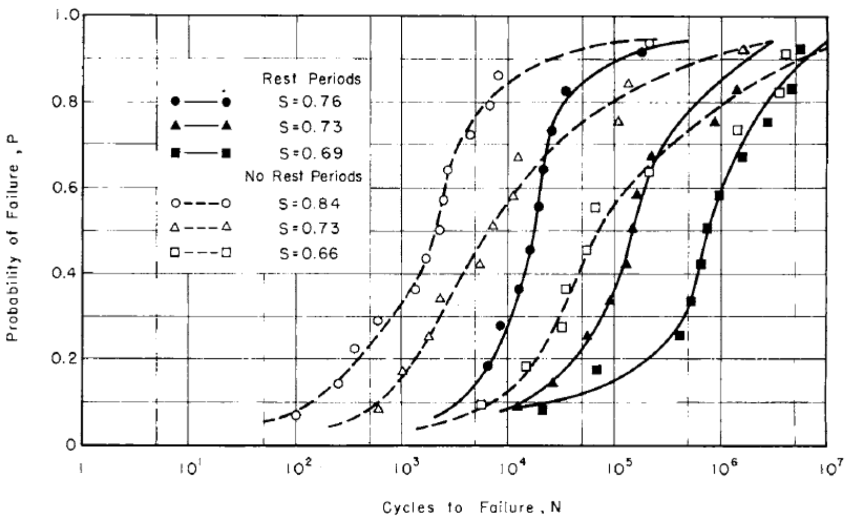


Figure 33: Probability of failure at a given number of cycles [61]

Some of the values show more difference than other. This can be illustrated by using the curves with mean stress of 0.73 as examples. The probability of failure before 10^4 is about 60% without rest periods. However, it drops to about 10% with rest periods.

A book by Neville[20] concerning the properties of concrete, reports on the findings by Murdock[63]. Neville reports a proportional relation between the strength increase and rest durations up to 5 minutes. Moreover, the benefit of the resting periods seem to depend on the loading frequency. The proposed explanation for the observed effect is related to the relaxation of bonds in the concrete, where these bonds may return to their original state as long as they are not broken[20].

Wu and Hachiya[64] reported similar findings when assessing pure concrete specimens exposed to bending. The mean flexural strength of these specimens was $4.97N/mm^2$ with a w/c ratio of 0.45. They found the resting periods to be beneficial provided that $S_{max} < 0.9$. This can be seen from Figure 34. The proposed explanation from Wu and Hachiya for this effect is adopted from Mallett[65]. He explains that longer rest periods allow stress redistribution and strain reversal, which combined give an increase in fatigue life[64].

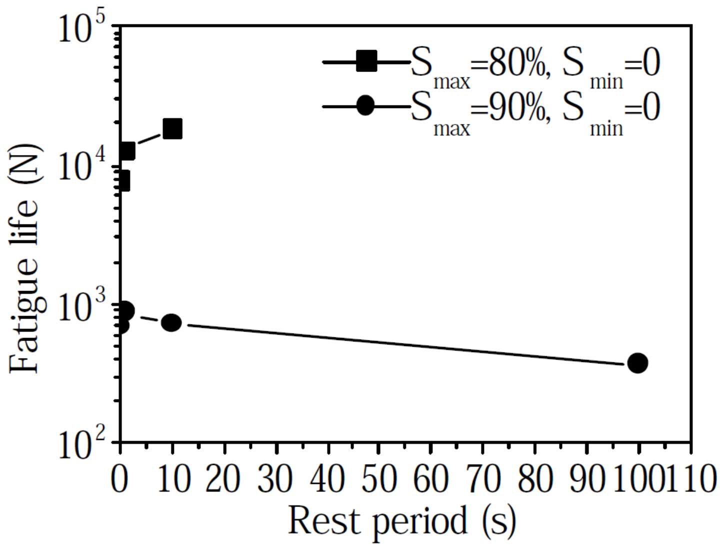


Figure 34: Effect of rest periods upon fatigue life[64]

Although a couple of studies have found rest periods to be beneficial, others have found it to have the opposite effect. Farhani [66] studied the influence of rest periods on concrete cylinders submerged in water. Most of his specimens were LWA, but he also included normal density concrete (NDC) for comparison. Two different pressure states were defined for the specimens submerged in water. One state had negligible confining pressure from the water, while the other had 7 MPa. The tests were conducted on concrete with ages of 1156 and 472 days for the LWA and NDC, respectively. S_{max} was set to 0.7 and S_{min} to 0.05, with a sinusoidal load of 1 Hz. When resting periods were introduced, a constant load of the mean stress level S_m was applied. The resting periods were of equal length to the cyclic loading. This can be seen in Figure 35.

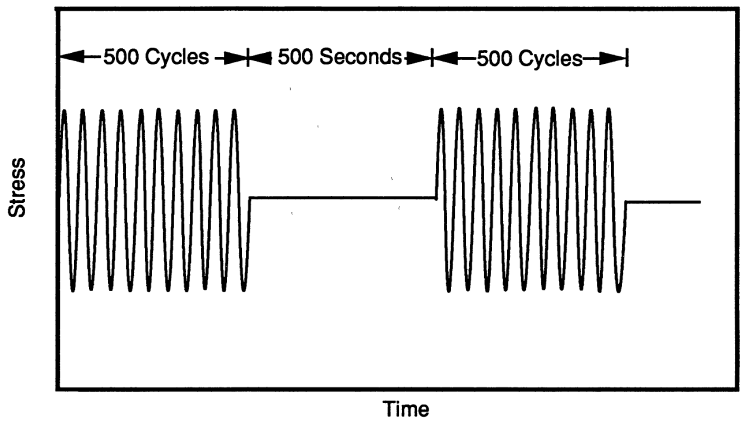
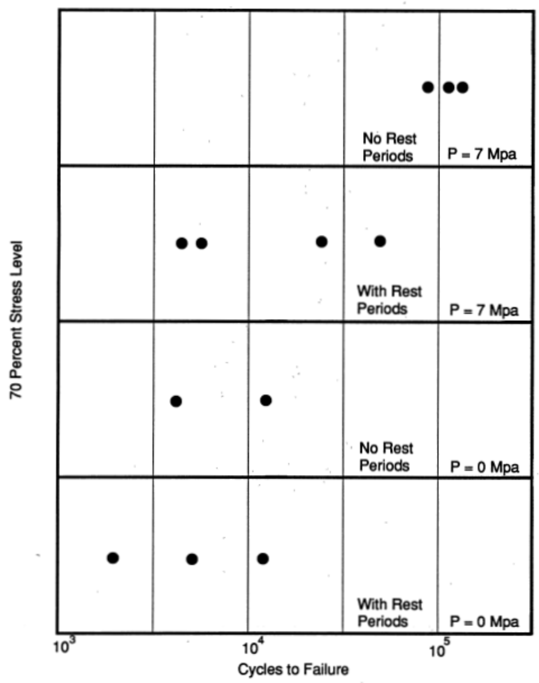
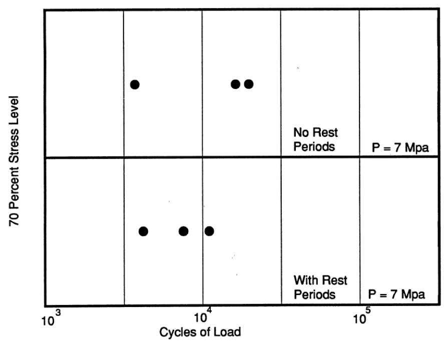


Figure 35: Loading history from Farhani[66]



(a) LWA



(b) NDC

Figure 36: Results from tests with and without rest periods[66]

Farhani[66] identified a decreased fatigue strength as a consequence of resting periods. This is shown in Figure 36, where both LWA and NDC exhibit the same tendencies. However, the fatigue strength of LWA concrete is especially influenced by rest periods when water pressure is large. At negligible water pressure, the effect on fatigue life of the LWA specimens is still considerable and causes a reduction of approximately 30%.

The resting periods in Farhani's tests were rather large (500s), compared to an earlier investigation. This choice was based on the results from Viswanathan[67], who conducted similar tests with rest periods of 9 and 99 second and found no effect of the rest periods. Farhani[66] assumes that the decrease in fatigue capacity is due to increased water ingress resulting from large resting periods. This is somewhat substantiated by his study. The elasticity modulus of the concrete was found to exhibit an increased stiffness after rest periods. This is probably caused by water in pores and voids, yielding initially increased stiffness. However, the water shorten fatigue life as discussed in Section 3.5.

The interaction between water and rest periods illustrates the complexity of concrete fatigue and the need for caution when translating the effects into design considerations. A summary of the studies of rest periods is given in Table 7.

Table 7: Investigations of rest periods with respect to fatigue

Author	**Rest length**	**Noticed effect**	**Notes**	**Year/ Source**
Neville(Murdock)	Various	Strength increase is proportional to rest periods up to 5 min		1960[20, 63]
Hilsdorf and Kesler	1,5,10,20 and 27 min	Extended fatigue life with rests up to 5 min, longer periods yield no further effect		1966[61]
Viswanathan	9 and 99 sec	No effect	Specimens submerged or moist	1982[67]
Mallett		Possible explanation for effect of rest periods based on redistribution and strain reversal		1991[65]
Farhani	500 sec	Damaging effect of rest periods	Specimens submerged	1992[66]
Wu and Hachiya	0-100 sec	Resting periods increase fatigue life provided $S_{max} < 0.9$		2000[64]

3.7 Stress Gradients

A large number of fatigue tests have been performed on concrete beams exposed to bending. These are often evaluated and compared to pure compression tests. A direct comparison of results from these two methods assumes the difference in stress distribution to have a negligible effect on fatigue. This is seemingly not true as it has been found that the stress gradient influences fatigue life.

One of the early investigations of stress gradient was performed by Ople and Hulsbos [68]. They conducted static and cyclic compression tests with different eccentricities to induce different stress gradients. The test specimens consisted of concrete prisms and concrete cylinders. All specimens were plain concrete with 1.9 cm maximum aggregate size and a w/c ratio of approximately 0.6. They found that the stress gradient largely influenced the fatigue life. In addition, it was noticed that the effect of stress gradient was highly sensitive to S_{max}. The results of Ople and Hulsbos are shown in Figure 37. It is clear that the uniform loading is most damaging, while an increased amount of eccentricity is beneficial for fatigue life.

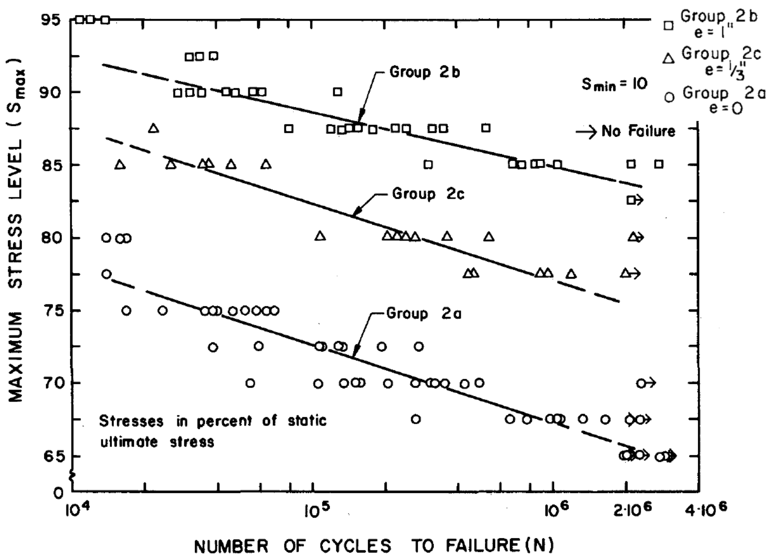


Figure 37: Stress gradient results by Ople and Hulsbos[68]

The results of Ople and Hulsbos are in agreement with the results from Cornelissen [69], who focused on the tensile fatigue behaviour of concrete. Cornelissen also concluded that stress gradients increased fatigue capacity. He referred to the explanation for this phenomenon given by Dillmann[70]. Dillmann argued that applied stress gradient causes a strain gradient. This strain gradient causes some fibers to have greater strain. In these fibers, stress relaxation will occur. Consequently, the stresses are redistributed to less strained fibers. This effect is relevant for both tension and compression and is found to be more pronounced with increased stress gradient[69]. The results of the tension-compression tests by Cornelissen are summarized in the SN curves shown in Figure 38. These show that the flexural specimens endured more load cycles for various stress levels compared to pure tension.

It is also noteworthy that the regression curves in Figure 38 change with different

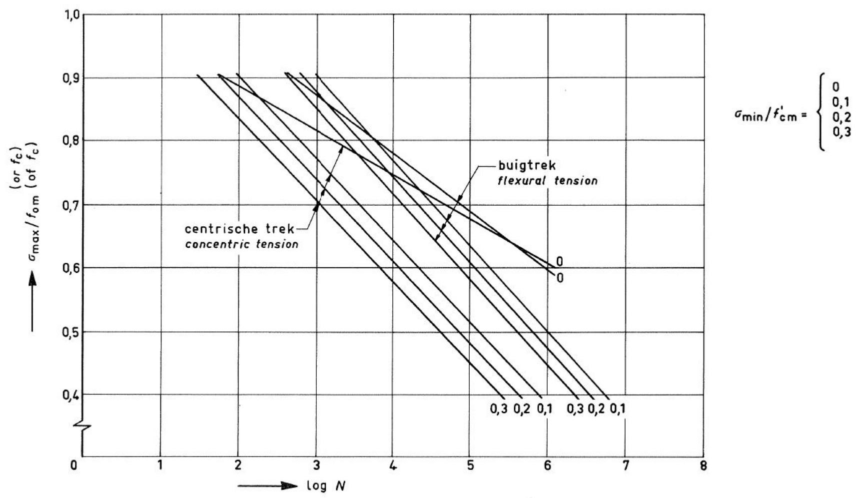


Figure 38: Influence of stress gradient by Cornelissen[69]

minimum stress levels. For all curves but $S_{min} = 0$, the change in S_{min} merely causes a shift along the x-axis. For $S_{min} = 0$, it changes the slope of the SN curves. As a results, the centric loading curve intersects with the flexural at $N = 10^6$. In other words, it appears as the minimum stress level annuls the effect of stress gradient. The change in slope is due to the loss of stress reversal effects as this is a case of pure tensile cyclic loading. In the regression analysis, Cornelissen included runouts. Consequently, there is some uncertainty in the final values of the regression lines. This gives conservative values, but yields little insight into the true behaviour and effect of stress gradient at higher cycles. Nevertheless, the tendency is clear for the examined range of cycles: a stress gradient yields beneficial results for fatigue in both compression and tension[68, 69]. A summary of studies of stress gradient is shown in Table 8.

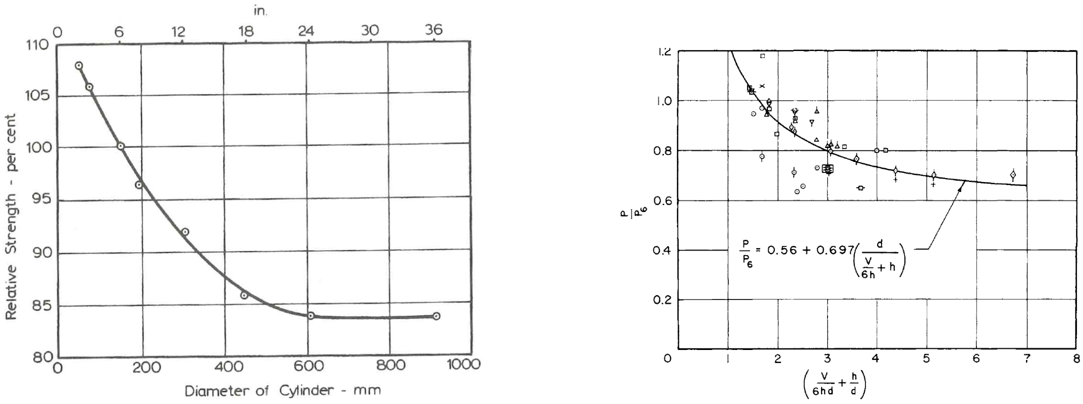
Table 8: Investigations of stress gradients with respect to fatigue

Author	**Stress gradient in**	**Noticed effect**	**Notes**	**Year/ Source**
Ople and Hulsbos	Compression	Stress gradient increased fatigue life		1966[68]
Cornelissen	Tension	Stress gradient increased fatigue life		1984[69]

3.8 Size Effect

The size effect is mostly treated in papers concerning fracture mechanics and the modeling of concrete fatigue. Diving into the topic of fracture mechanics would require extensive derivations which is beyond the scope and intent of this thesis. However, a look at the fracture mechanics behind the size effects is included. The issue of size can also be associated with the issue of moisture content as discussed in Section 3.5. The moisture state is highly influenced by the water evaporation, where a larger specimen tends to have a slower evaporation rate. Another size effect not specifically related to cyclic loading and fatigue, is the one mostly discussed in relation to monotonic strength testing.

The general tendency of the size effect in monotonic load application is that an increase in specimen size results in a decrease in strength. "Strength" might refer to several stress states, including compression, tension and modulus of rupture. An intuitive explanation for this effect is provided by Neville[20]. As concrete consists of several components with variable strength, the likelihood of a specimen containing elements of extreme low strength increases with specimen volume [20, p.604]. The probability of defects in the material structure leading to these low strength areas is dependent on the material constitution and curing conditions, where nonuniformity in material is a large contributor. The size effect has limits and at a certain point larger specimens yield no further strength reduction[20, p.609]. This is visible in Figure 39. Figure 39a shows that the size which give no further strength reduction is quite large. Furthermore, the final strength reduction may be quite substantial, which can be seen from both Figure 39a and Figure 39b.



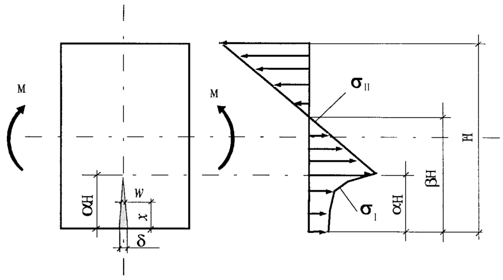
(a) Size effect on cylinder compression strength[71]

(b) Size effect estimation by Neville for static compression loading[72]

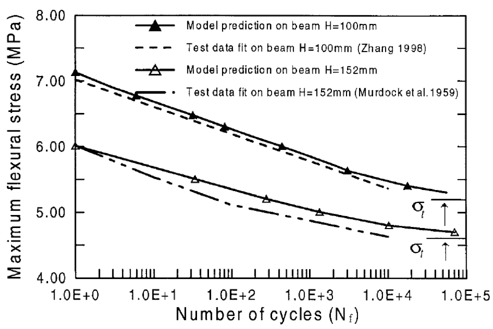
Figure 39: Size effect on compression specimen

As mentioned at the start of this section, most studies involving size effect in fatigue are from fracture mechanics. These investigations focus on the development-rate of cracks. An example is the study by Zhang et al.[73], which established a model for fatigue life prediction of cracked concrete beams. This model assumes that a crack has formed in the section. It is the further crack propagation that is relevant for the model. This sort of model is therefore highly relevant for predictions of remnant fatigue life. A short segment of a beam and an assumed stress distribution at the point of crack formation is the basis of their model. This basis is shown in Figure 40a. Despite the formation of a crack, the crack area is considered to withstand some stresses due to crack bridging. This means that, some of the aggregate is believed to enable transfer of stresses through the crack.

Zhang et al.[73] developed an empirical expression to account for the degradation of the crack bridging effect. This expression describes the stress distribution in the crack, σ_I, as a function of load cycles. Next, Zhang et al. applied equilibrium



(a) Size effect fracture model basis by Zhang et al.[73]



(b) Comparison of Zhang et al model by result from Zhang and Murdock

Figure 40: Investigation of size effect by Zhang et al.[73]

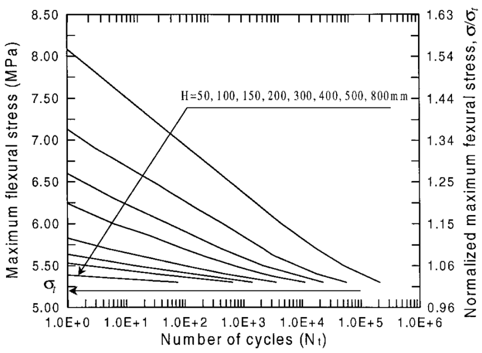
equations as well as empirical equations for the crack mouth opening displacement (CMOD), to form the mathematical equations for their model. This yielded three equations, shown in Eq.2, 3 and 4. The last expression is developed by Tada [74] and describes CMOD. To keep the derivations short, a complete insight into the equation of Tada will not be given here. The interested reader is referred to the paper by Zhang et al.[73] or the book by Tada [74] for a more thorough derivation. The three nonlinear equations were solved using an iterative numerical method to determine crack length and CMOD.

$$\int_0^{\alpha H} \sigma_I(x)\, dx + \int_{\alpha H}^{H} \sigma_{II}(x)\, dx = 0 \tag{2}$$

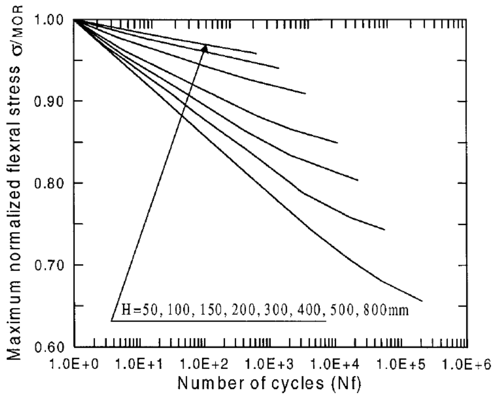
$$\int_0^{\alpha H} \sigma_I(x)(H-x)B\, dx + \int_{\alpha H}^{H} \sigma_{II}(x)(H-x)B\, dx = M \tag{3}$$

$$\delta = \frac{24\alpha}{BHE}[MV_1(\alpha) - M'V_2(\alpha)] - \frac{4\sigma'\alpha H}{E}V_3(\alpha) \tag{4}$$

Zhang et al.[73] did not perform any tests on their own, but used tests from other researchers to verify their model. This is shown in Figure 40b. The comparison shows a good fit with the experimental results from Murdock [75] and Zhang [76]. Zhang et al.[73] simulated eight differently sized beams to show the difference in fatigue capability. The simulations assume that the model is valid for a large range of specimen sizes. The simulations are summarised in Figure 41a and illustrate that the size effect decreases fatigue life of larger specimens. This conclusion is only valid for absolute stress, and not stress relative to the static modulus of rupture (MOR). If stress is normalized with respect to MOR, which is also size dependent, the effect reverses. Consequently, a larger beam would withstand a larger number of cycles compared to a smaller. This can be seen in Figure 41b. In general, the size effect decrease fatigue life with increasing specimen size. This is also shown in Table 9.



(a) Beam simulations on size effects[73]



(b) Beam simulations on size effects normalized with static MOR[73]

Figure 41: Beam simulations by Zhang et al.[73]

Table 9: Investigations of size effect with respect to fatigue

Author	**Sizes considered**	**Noticed effect**	**Notes**	**Year/ Source**
Zhang et al.	50, 100, 150, 200, 300, 400, 500 and 800 mm	Similar strength reduction with larger specimens as seen in static application	Only considered for bending application	2001 [73]
Kirane and Bazant	40, 93 and 21 5mm height	Decreased fatigue life with increasing specimen size verified through tests	Three point bending test	2016[77]

3.9 Amplitude and Stress Reversal

As described in Section 3.1, the stress level is usually of greater importance than the amplitude when considering fatigue. However, the importance of stress range (amplitude) is not negligible. The amplitude is an important parameter for separating cyclic and sustained load effects. The amplitude and its influence on fatigue life is one parameter included in nearly all fatigue studies. However, most limit the discussion to a confirmation of the general expected result. The characteristics of amplitude effect on concrete fatigue is similar to those found for steel and various other material; an increase in amplitude tend to reduce fatigue life. This happens to be true for both compression and tension[12].

One of the early investigations of amplitude influence was performed by Murdock and Kesler[75] in 1958. They studied plain concrete beams subjected to bending loads. They found a clear connection between stress range and fatigue life. This can be seen in Figure 42. Different stress ranges, expressed through the stress range ratio, $R = \frac{S_{min}}{S_{max}}$, yield different capacity curves.

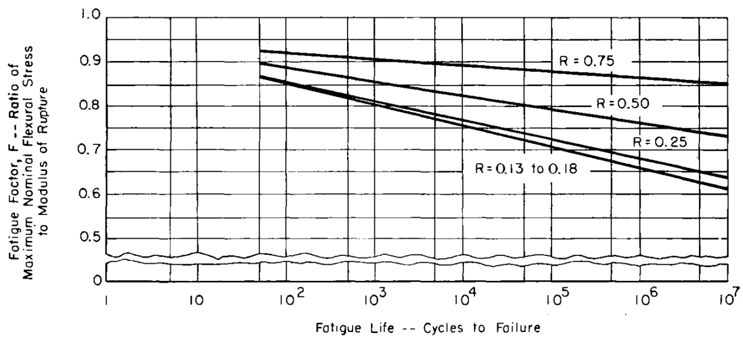
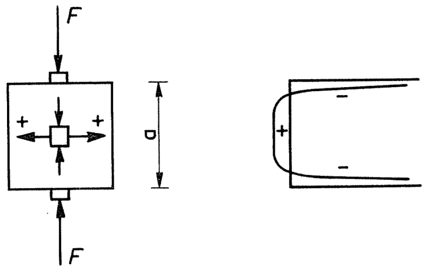
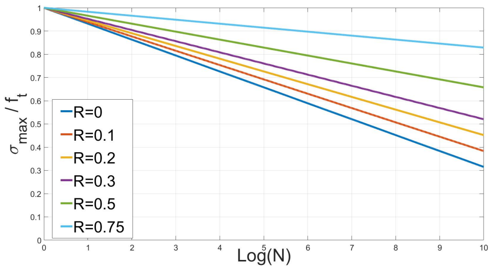


Figure 42: Effect of stress range on fatigue life in compression[75]

A similar relation between stress range and tensile fatigue loading was found by Tepfers[78] in 1978. He performed tests of 48 concrete cubes in order to investigate if the logarithmic linear relationship proposed by Aas-Jacobsen could be extended to tensile fatigue. The splitting test was deemed the most appropriate due to difficulties with loading in pure tension. Tepfers assumed that the compressive stresses in the specimen were negligible, despite the expected stress distribution as shown in Figure 43a. This assumption is based on the estimation of static reference strength with the same stress distribution. His results showed that the Aas-Jacobsen formula gave a good fit when stress was expressed as a ratio of the static tensile strength. The influence of the stress range is, as shown in Figure 43b, in good agreement with the results from compression tests.



(a) Splitting test stress distribution [69]



(b) S-N curves for splitting tension according to Tepfers [78]

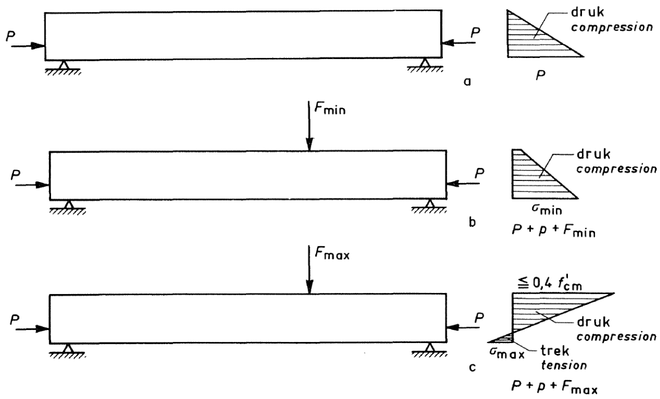
Figure 43: Stress range effect in tensile cyclic loading

Several studies have expanded the stress range and investigated the effect of stress reversal, where the loading becomes an alternating tension-compression loading. The effect of stress reversal have for instance been studied by Tepfers [79] and later by Cornelissen[69] and Zhang et al.[36].

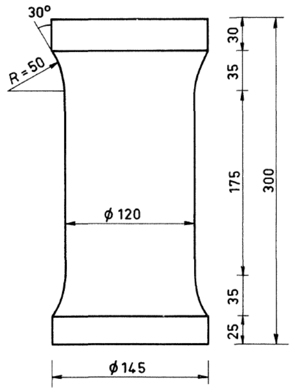
In 1982, Tepfers[79] published a paper concerning the treatment of stress reversals. The hypothesis was that tension and compression degrade the concrete differently by causing crack propagation in opposite directions. It was assumed that these damages were not additive. This means that the maximum relative stress level, from either compression or tension, is the parameter of interest.

Tepfers tested his hypothesis on 56 cubes with side lengths of 15 cm and 29 cubes with sides lengths of 20 cm, and static compressive strengths in the range 28-70 MPa. The cubes exposed to stress reversal showed more scatter than the pure compression cubes. Tepfers attributed this difference to the loading arrangement, where tension is more difficult to load uniformly compared to compression. The test results did not explicitly show that tension and compression degrade concrete differently. This is due to the presence of additional strength reduction caused by alternating forces. Hence, the effect of stress reversals was quite small and influenced by uncertainties resulting from the loading arrangement. Consequently, it was difficult to state the actual importance of this effect. Nevertheless, the experiments indicated some effect of stress reversals beyond a simple expansion of stress range.

Cornelissen[69] mainly focused on tension capacity of concrete and tested this using bending and pure tension. He also tested the effect of stress reversals. However, the compression levels was kept low in order to avoid compression failure. To enable alternating stresses, the test setup for bending involved prestressed beams with length of 2.1m. The concentric tension tests was simple 300mm long cylinders with metal plates bonded at the ends. The test setups are shown in Figure 44.



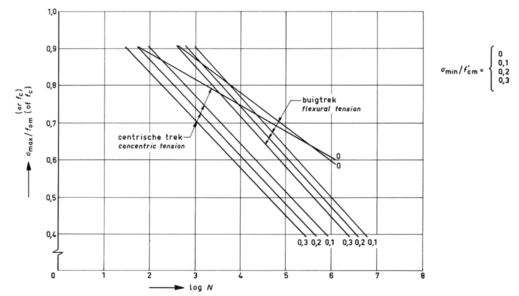
(a) Specimens for bending tests



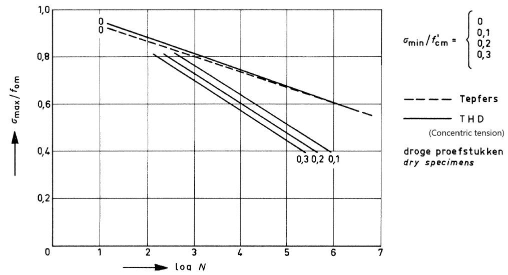
(b) Specimen for concentric tests

Figure 44: Tensile stress range test specimens[69]

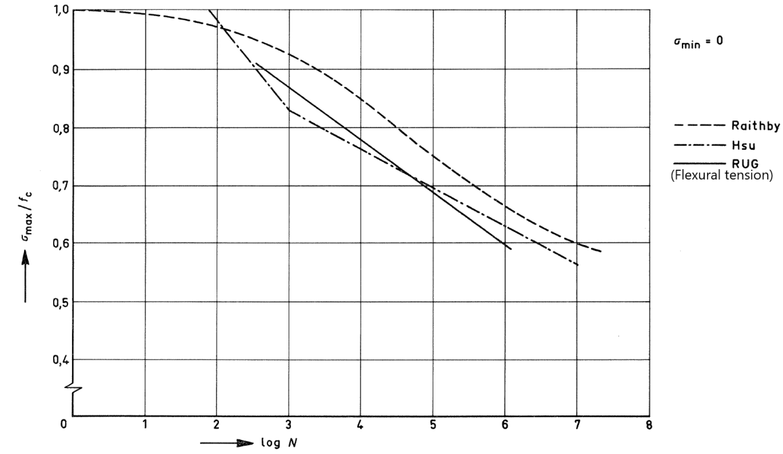
The results of Cornelissen[69] is summarized in Figure 45a, which was also included in Section 3.7. It should be noticed that the change in the curve inclination from stress reversal to cyclic tension changes in Figure 45a. This change applies for both testing procedures and indicates that stress reversals yield additional effects beyond a simple expansion of the stress range. The inclination of the pure tensile curve is also similar to the proposed compressive curve by Hsu[11] and the tensile curve by Tepfers[78] as shown in Figure 45b and 45c. This might suggest that cyclic tension and cyclic compression have similar effects on the degradation rate of concrete.



(a) Results from Cornelissen, both tension and flexural



(b) Pure tension results compared to results by Tepfers



(c) Flexural tension results compared to Hsu and Raithby

Figure 45: Stress reversal effect from cornelissen, with comparions [69]

The paper presented by Zhang et al.[36], mentioned in Section 3.3, analyses the effect of stress reversals and attempted to quantify it. Zhang et al.[36] tested 171 beams to determine the influence of stress reversals. These results, in addition to tests from other researchers, were compared with a proposed equation. The equation fitted well when $R < 0.75$, as shown in Figure 46. Zhang et al. explained this discrepancy based on a paper by Hsu[11]. For large amplitudes, the cyclic loading acts similarly to sustained loading. As a result, the sustained loading effects may dominate the fatigue process.

The comparisons showed that stress reversals give some reduction of fatigue life. However, the effect is limited. The decrease in capacity is major with larger amplitudes in the range $0 < R < 1$. Expansion to negative values of R yields comparatively less. This can be seen from Figure 46 where the equation is shown for different values of R.

All studies are in agreement on the effect of stress range. An increased stress range decreases the fatigue capacity in all cases. A summary of the investigations of stress range and reversals is given in Table 10.

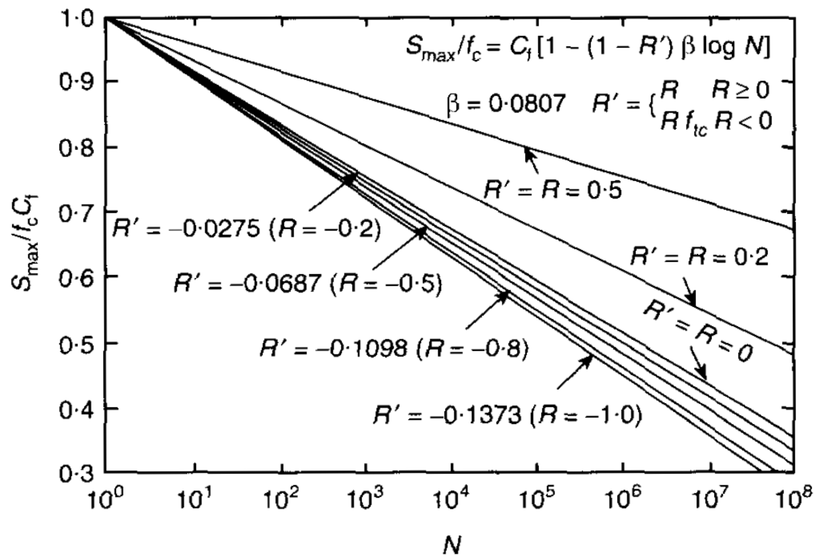


Figure 46: SN curves for different values of R'[36]

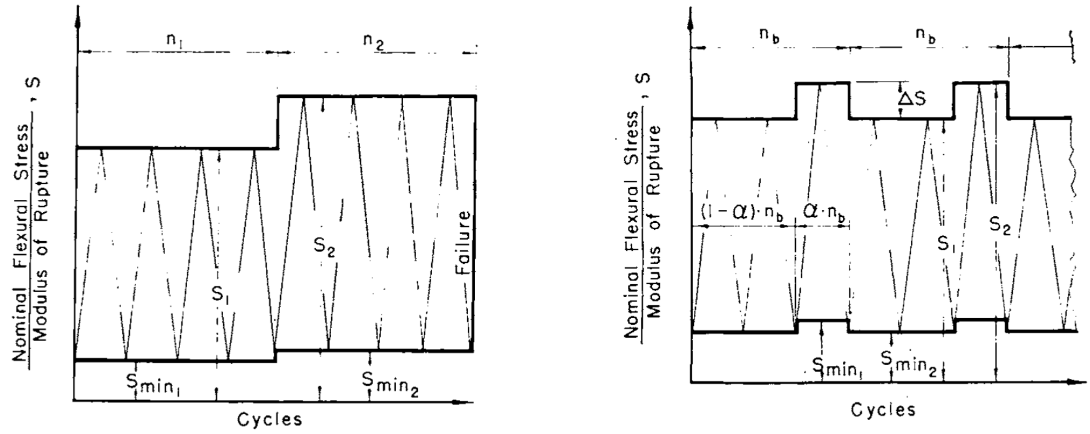
Table 10: Investigations of stress range and stress reversals with respect to fatigue

Investigation	**Author**	**Noticed effects**	**Note**	**Year/ Source**
Stress range	Murdock and Kesler	Larger amplitude reduces fatigue life	Compression	1958[75]
Stress range	Tepfers	Larger amplitude reduces fatigue life	Tension	1978[78]
Stress reversals	Tepfers	Some additional damage due to stress reversals	Some uncertainties in loading arrangement	1982[79]
Stress reversals	Cornelissen	More damage due to stress reversal beyond the expectation from a simple expansion of stress range.		1984[69]
Stress reversals	Zhang et al.	Limited additional damage by exposure to stress reversals		1996[36]

3.10 Multiple Stage Loading

So far, only single stress range or single amplitude tests have been considered. However, the full influence of stress range cannot be unveiled by merely studying these in isolation.

The effect of variable stress range was studied by Hilsdorf and Kesler[61] on the flexural strength of concrete beams. They studied the effect both in it simplest form with only two stress ranges, and for more complex loading series. This is shown in Figure 47.



(a) Two stage load series

(b) Multiple load series

Figure 47: Load series by Hilsdorf and Kesler[61]

The loading series shown in Figure 47a were partitioned into two programs, with constant R= 0.17:

1. Increasing the stress range from S1 to S2
2. Decreasing the stress range from S2 to S1

Hilsdorf and Kesler[61] compared the expected number of cycles for a certain load N_i to the observed number of endured cycles. This is shown in Figure 48. When loading cycles n_1 approaches N_1, n_2 generally approaches zero. However, the linear Palmgreen-Miners hypothesis fails to approximate the fatigue capacity in-between the boundaries. The tests by Hilsdorf and Kesler[61] show that fatigue life is largely dependent on the order of the stress ranges. An increase in stress level on the subsequent stress range, yielded a decrease in fatigue life compared to the P-M rule. When a decrease in stress level was applied, the fatigue life became larger than expected from the P-M rule.

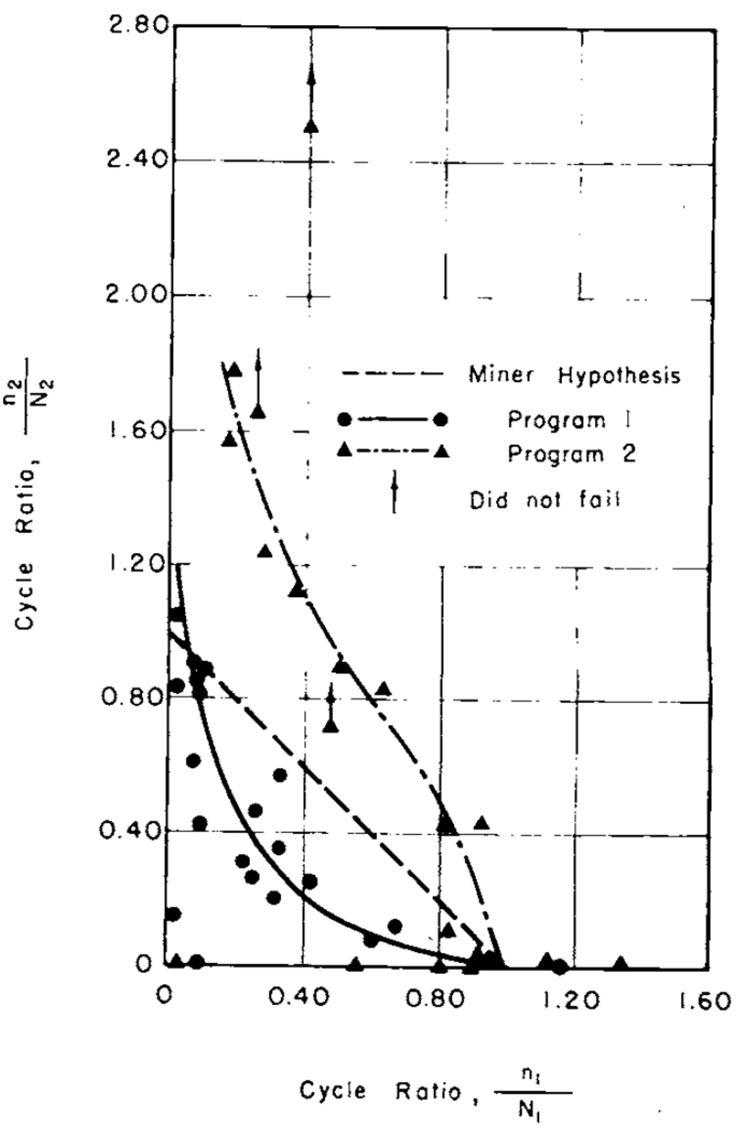


Figure 48: Result of two stage load series by Hilsdorf and Kesler [61]

Hilsdorf and Kesler[61] partitioned the multiple load series into five different combinations in order to study two variables:

1. α, the ratio of cycles in higher stress level (S_2) to the total amount of cycles
2. ΔS, the difference in the two applied maximum stress levels

Hilsdorf and Kesler[61] points out that the multiple loading series exhibit some of the same tendencies as the two-stage loading tests. Some of the results from the multiple loading series are shown in Figure 49, illustrating the tests with the loads from Figure 47b. These tests have relatively low α value, meaning that the dominant cycle in the stress block consists of the lower stress level(S_1). The results show that the tests exhibited increased fatigue life for cycles above 10^5 compared to the P-M rule. For specimens failing below 10^5 cycles, the fatigue resistance is less indicated by the P-M rule. Hilsdorf and Kesler believed that this behaviour partly emerged from the changes of the relative stress level of the specimens with time. This means that several sustaining cycles allow the actual concrete strength to increase, thereby reducing the actual relative maximum loading.

Hilsdorf and Kesler[61] believed that residual stresses naturally present in the specimens, due to drying shrinkage, caused a reduction in their tensile capacity. When a bending load was applied at a stress level which did not induce damage, a permanent deformation was still detected. This deformation was believed to take place in the cement paste, inducing stresses of opposite sign compared to those from shrinkage. By this mechanism, the cyclic load might relieve the residual stresses and give a strength increase. The extent of this alleviation was assumed to be dependent on the stress level and the number of cycles, where a larger loading causes a larger strength increase. However, a larger loading is also known to cause more damage per cycle than a smaller loading. Hence, the benefit from a larger loading has to be compared to the disadvantage of larger damage.

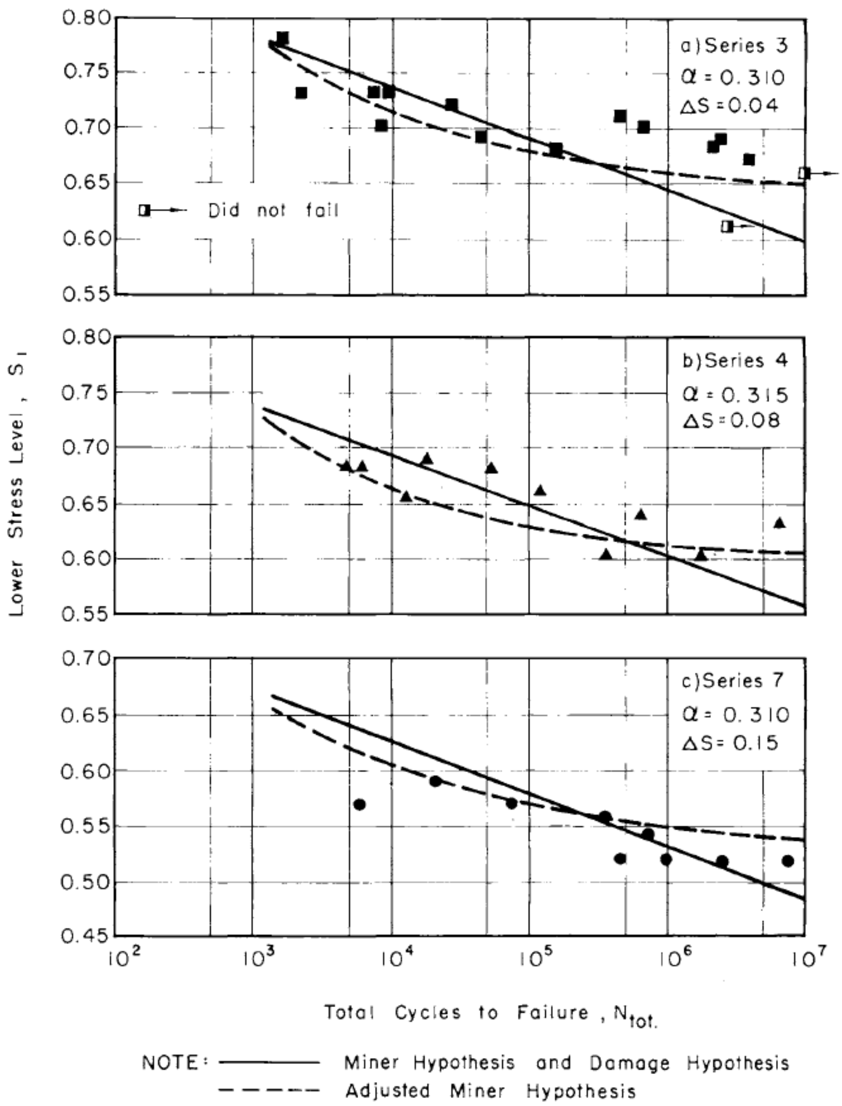


Figure 49: Results from multiple load stage tests by Hilsdorf and Kesler[61]

Hilsdorf and Kesler created a simple model to explain their findings. The proposed model is shown in Figure 50. In the figure, the loadings are not the same as earlier.

The model assumes S_1 to be the largest and S_4 the smallest loading. A thorough explanation, with an example, is given in the paper by Hilsdorf and Kesler [61]. Consequently, a short summary is deemed to suffice here. In Figure 50, several curves are shown indicating the damage (d) for a certain number of cycles (n) and stress levels S_i (i=1,2,3,4). Below the abscissa, the function for strength increase is shown. These two parameters are the basis of the "true" strength of the specimen. For lower number of cycles, the strength is increased compared to a static reference value. This increase is more pronounced for high stress levels. This explains why a high stress level applied early in the fatigue life yields a beneficial effect. The issue with the model presents itself when switching from a high stress level (S_1) to a lower level(S_2). The change in "true stress level" during S_1 has to be accounted for when approximating the damage of S_2. Hilsdorf and Kesler assumes this change in "true stress level" also changes the damage curve of S_2. Hence, the damage curve for S_2 loading after S_1 is likely to follow approximately the damage curve of S_3. The damage curve S_3 would have to be found experimentally. Hence, to utilize this method in design would require large datasets.

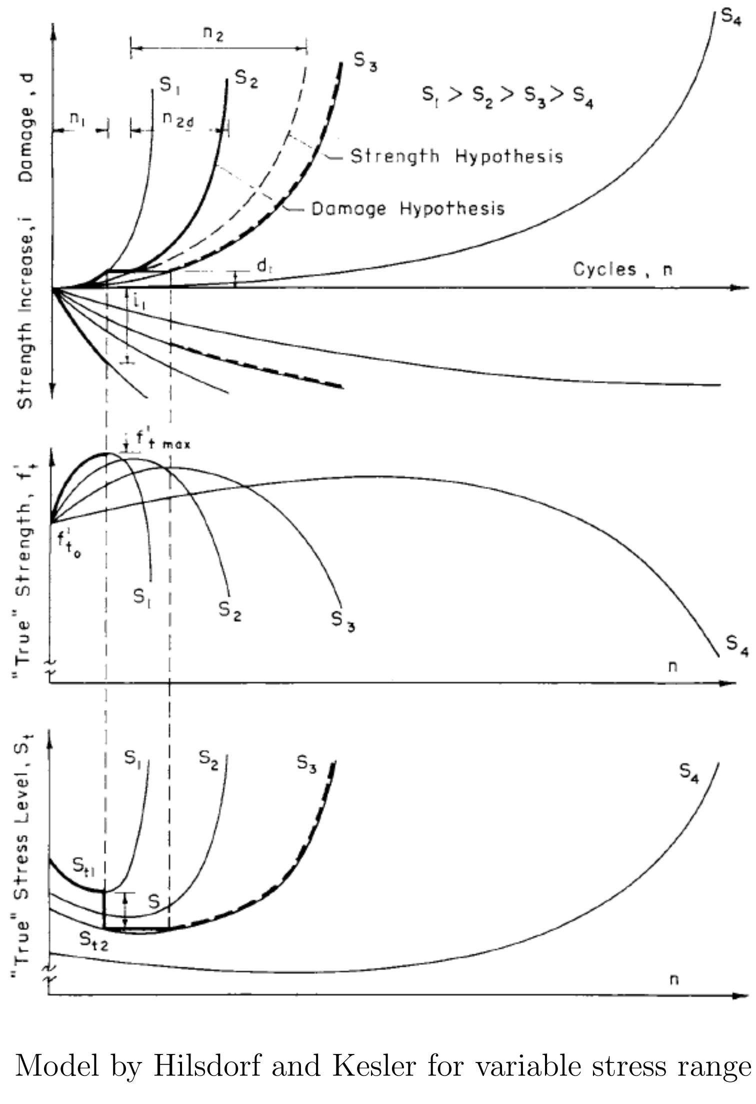
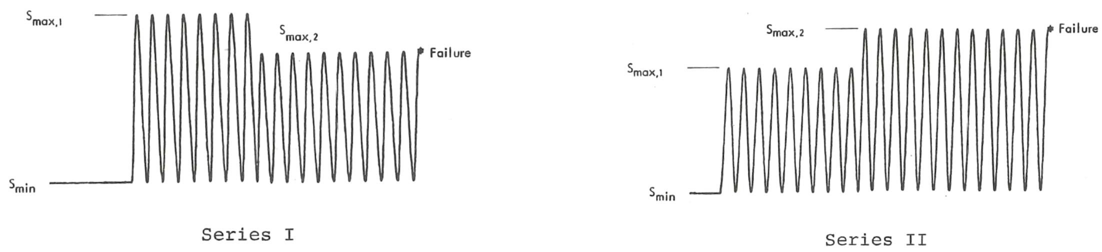


Figure 50: Model by Hilsdorf and Kesler for variable stress range effects [61]

Hordijk[80] applied pure tensile loading to plain concrete specimens and found the same sequence effect as Hilsdorf and Kesler. However, an investigation by Oh[81] found a different trend. He tested plain concrete beams in four-point bending. The beams were exposed to two and three stage loading, either increased S_{max} with each stage or decreased S_{max}. Both the two stage and three stage tests showed that an increase in S_{max} yielded longer fatigue life. A decrease in S_{max} on the other hand, decreased the fatigue capacity compared to the P-M rule. A very large scatter was found in the results. The two stage loading with increasing load, had a minimum miner sum of 0.38. This is in agreement with the results by Hilsdorf and Kesler[61]. The maximum miner sum was 2.59. The tests had a mean sum of 1.33, with five of the specimens with miner sums below 1 and 7 with sums above 1. Thus, concluding on the results by Oh[81] is challenging, although the mean trend contradicts Hilsdorf and Kesler's[61] results.

Holmen[21] did similar two stage loading tests, as Hilsdorf and Kesler[61], although on cylindrical specimens loaded in pure compression. The aim of his investigations was to assess the validity of the PM-hypothesis on concrete structures. However he used a limited number of specimens to test the hypothesis. Two different load series were tested. One serie had first a high amplitude then a low. The other serie used the opposite test setup. The series are shown in Figure 51.



(a) (b)

Figure 51: Two stage load series by Holmen[21]

The tests used 5Hz loading frequency and set S_{min} to 0.05 and S_{max} to either 0.75 or 0.9. Holmen concluded that P-M rule is unsafe when stress level is decreased and conservative if the stress level is increased. This is the opposite behaviour of the findings by Hilsdorf and Kesler[61] on two stage loading. Although Holmen[21] only tested 10 specimens in his two stage loading configuration, his results are in agreement with Jinawath[6] who performed similar compression testing on cylinders with two stage loading. Both Holmen[21] and Jinawath[6] reached the same conclusion: Going from a high stress level to a low stress level decreases fatigue life and the P-M rule is thus unsafe.

Tepfers et al.[82] also performed a study of the applicability of the PM-hypothesis to concrete structures by exposing concrete cylinders to two stage cyclic loading. Their results did not contradict the estimates of the PM-hypothesis, despite some scatter. At the same time, their results showed some of the same tendencies as Holmen[21] and Jinawath[6]: large loading followed by smaller loading give a reduced fatigue life compared to linear summation. Tepfers et al.[82] also reports on the finding of Weigler and Freitag studying lightweight concrete in compression, where no effect of the loading order was found.

The results of Tepfers et al.[82] exhibited large scatter. Some possible reasons for this scatter have been explained by Bennett[83]. In his contribution, he reports on results, from Jinawath[6], where a clear influence of loading order is visible. This is shown in Figure 52. Bennett argued that much of the scatter in the results of Tepfers et al. was due to the small cylindrical specimens(25x50mm). In comparison, the tests from Jinawath[6] used concrete prism (203x76x76mm), Hilsdorf and Kesler[61] used beams (150x150x1500mm) and Holmen[21] used cylindrical specimens (100x250mm).

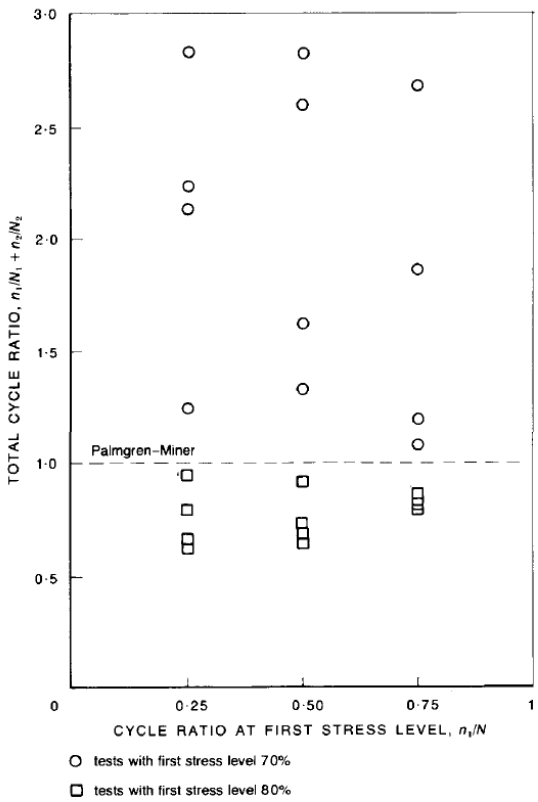


Figure 52: Two stage loading investigations from Bennett[83]

Hoff et al.[84] investigated the effect of LWA concrete in compression. Their experiments showed the same effect as described by Holmen[21]. Hoff et al.[84] found that a high load followed by a low load yielded a mean miner sum of 0.68, thus a decreased fatigue life. The reversed order yielded a miner sum of 2.19.

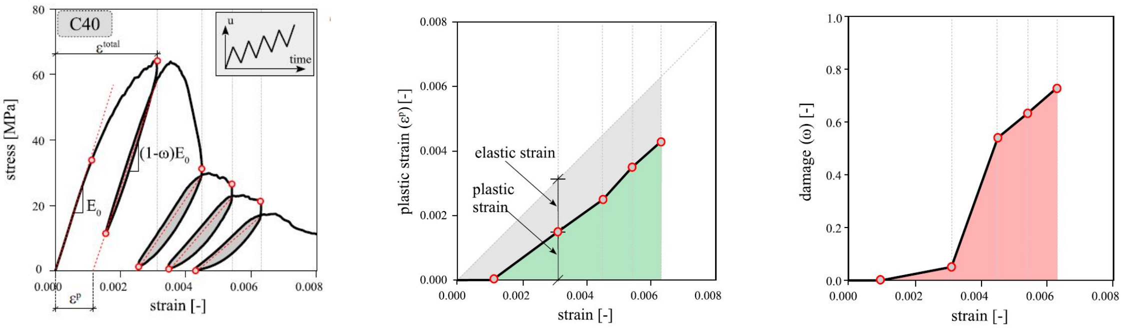
The discussed studies show discrepancies in the results of loading order, where tensile tests differ from compression tests. The issue was briefly mentioned by Bennett[83] in the contribution to Tepfers et al.'s paper[82]. Bennett did not reach a conclusion for the existence of this discrepancy. He merely stated the importance of caution when findings are reported. Hilsdorf and Kesler[61] emphasised the importance of duration of the loading sequences to determine whether it might be beneficial or harmful. Hence, some of the explanation for conflicting results may lie in the difference in test parameters.

Bennett[85] does provide an explanation for the sequence effect in compression, as his tests showed the same sequence dependency as Holmen[21]. Bennett[85] argues that this effect may be caused by a large amount of fine cracks appearing during cyclic loading. These fine cracks are allowed to form in larger extent when small cyclic loads are used than if larger cyclic loads are used. Large cyclic loads however, could potentially cause less but more severe cracks. When the subsequent loading of a higher stress level is applied, the existence of a large number of fine cracks spread the crack propagation over more of the existing cracks. Consequently, the fatigue life may be extended.

A more recent investigation of multiple stage loading has been conducted by Baktheer and Chudoba [41]. Their study consists of both experimental and theoretical analysis to explain the phenomenon of sequence effects. They used plane concrete cylinders with various strengths (C40/50, C80/90 and C120). The specimen sizes ranged from a diameter of 100 to 150mm with a total height of 300mm. The specimens were loaded in pure compression. The two stage loading program revealed the same sequence effect as found by Holmen[21], namely that the P-M rule underestimates fatigue life when low stress is followed by high stress. The opposite loading arrangement causes overestimation. The aim of the tests from Baktheer and Chudoba was to assess and provide deeper understanding how damage accumulates inside the specimen. They regarded that there are two primary energy-dissipative mechanisms: plastic strains and stiffness degradation. Even though the plastic strain evolution may be seen as an indication of damage, Baktheer and Chudoba considered the damage as a function of stiffness degradation. They use Eq.5 to track the damage (ω), where E_0 is the initial stiffness and E is the stiffness at each point on the unloading branch of the stress-strain curve.

$$\omega = 1 - \frac{E}{E_0} \tag{5}$$

One of their loading scenarios applied repeatedly a constant deformation up until the point of stress decrease. This scenario showed another interesting trend in plastic strain accumulation and the development of the damage parameter (ω), as shown in Figure 53. The tests showed a clear distinction in the behaviour of damage development relative to strain development for the pre and post-peak, i.e. before and after maximum stress in Figure 53a. During most fatigue tests, at least when considering High cycle fatigue, the stress limits are in a subcritical range. This means a range where pre-peak behaviour is expected. In that range the plastic deformation is the major dissipative mechanism. This is shown in Figure 53b and 53c.



(a) Stress-strain relationship

(b) Plastic strain compared to total strains

(c) Damage propagation curve

Figure 53: The effect of cyclic deformation loading upon the dissipative mechanisms in concrete[41]

Plastic deformation is thought to be caused by plastic sliding along the aggregate interfaces. As aggregate is approximately uniformly distributed within the section, assuming evenly distribution of changes in the material structure is reasonable. This assumption enables Baktheer and Chudoba[41] to show that superposition of energy dissipation curves is a valid method. Their proposed explanation for the sequence effect is illustrated in Figure 54, where the specimen is able to dissipate a certain amount of energy regardless of loading. However, the trail taken to reach this limit changes with different load parameters. The actual experimental verification of this hypothesis is difficult to obtain. Furthermore, the assumption of evenly distributed energy dissipation within the specimen is not valid if the specimen exhibits crack localization. This tend to occur at least to some extent. In an earlier investigation Baktheer and Chudoba used a model which aimed at providing an alternative to the P-M rule[86]. This model exhibited a behaviour corresponding to energy superposition and was a good approximation of fatigue life and deformation behaviour of two stage loading. This model is elaborated on in Section 4.2, where the issue of damage accumulation design is discussed.

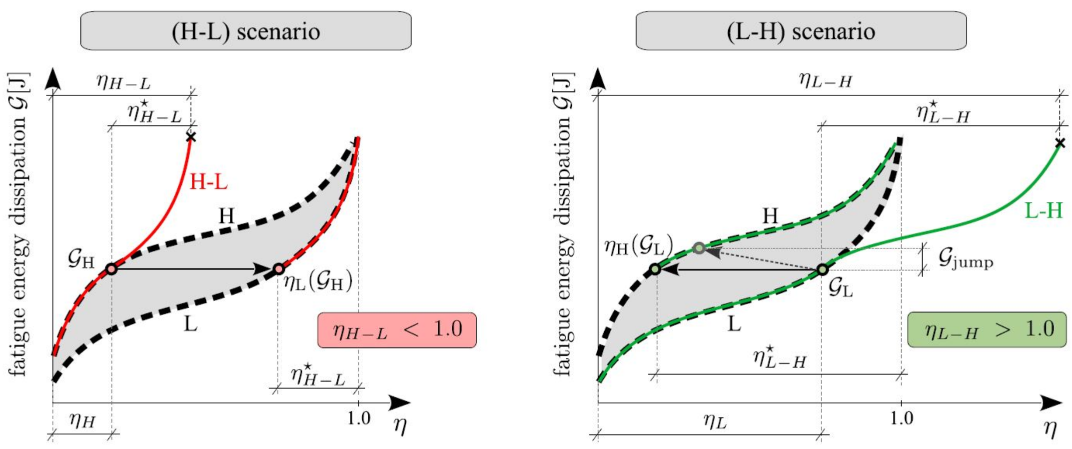


Figure 54: Explanation of the sequence effect by Baktheer and Chudoba[41]

The proposed explanation for the sequence effect by Baktheer and Chudoba[41] fits well for purely compressive tests with multiple stage loading. When tension is involved, the opposite sequence effect has been observed. Baktheer and Chudoba's explanation for this contradiction is based on the occurrence of damage localization during bending (tension). Thus, a superposition of strains is not a valid approach. The exact explanation for the sequence effect in tension is not given. However, it is suggested that a model considering the evolution of the inelastic state field during fatigue loading might offer a deeper insight.

The complexity of varying loads increases when more stages or random loading are introduced. As discussed earlier, Hilsdorf and Kesler conducted multiple load series tests and observed a complicated behaviour. This was shown for some of their tests in Figure 47.

Holmen[21] investigated the behaviour of plain concrete subjected to random load series. The load series were randomly generated by the use of stationary narrow banded Gaussian process assumption using pre-defined statistical properties of loading. The loading series were partitioned into three models:

- Model 1: Mean stress level kept constant for every loading sequence
- Model 2: Minimum stress level kept constant for all loading sequences
- Model 3: Combination of model 1 and 2 with constant minimum stress level but amplitudes equal to those of Model 1

These models were further partitioned into groups with certain additional limitations such as omitting very small, or very large peaks etc. The testing scheme from Holmen[21] is quite extensive and thoroughly documented in [21], and this thesis limits itself by referring to his findings.

In Table 11, the mean miner sums are of most interest as they are below one for all test. This means that the PM hypothesis overestimates the fatigue life of the specimens for every loading sequence. Holmen also found that small amplitudes in the loading histograms seemed to reduce the presence of sequence effects and improved the accuracy of the PM hypothesis. However, this was less pronounced in the tests from Model 1. Both Model 2 and 3 were set with a constant minimum stress level. This caused more damage than a constant mean stress level as in Model 1. Holmen gives no explanation for these observations, and concludes that further investigations are needed to determine the damage mechanism.

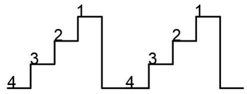
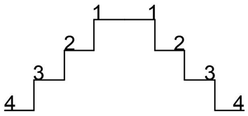
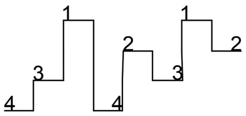
Table 11: Summary of the variable amplitude loading tests by Holmen[21]

LOADING HISTOGRAM	**MEAN MINER-SUM**	**90% CONFIDENCE INTERVAL FOR MEAN M**	**ES,80/ES,10**
Model 2, unmodified	0.59	0.43 -0.81	0.85
Model 2, small ampl. Omitted	0.28	0.21- 0.36	0.83
Model 3, unmodified	0.53	0.39-0.72	0.86
Model 3, small ampl. Omitted	0.39	0.27-0.53	0.83
Model 3, large ampl. Truncated	0.3	0.22-0.40	0.84
Model 1, unmodified	0.84	0.64-1.11	0.9
Model 1, small ampl. Omitted	0.75	0.52-1.06	0.89

The loading scheme by Holmen[21] is random. Hence, a comparison of his findings with the proposed rule by Baktheer and Chudoba[41] is difficult. However, Hümme et al.[53] performed three stage compressive tests on NSC with either decreasing (S_{max}=0.8, 0.7 and 0.6) or increasing stress levels (S_{max}=0.6, 0.7 and 0.8). Surprisingly, their tests contradict the proposed model from Baktheer and Chudoba[41]. The decreasing stress level setup yielded increased fatigue life. This is the reversed effect found in two stage compressive loading by Holmen[21] and several others [6, 29, 42, 82, 84]. This is an unexpected result since it goes against the sequence effect explanation provided by Bennet[85] and Baktheer and Chudoba[41]. Unfortunately, Hümme et al.[53] provided no explanation for their results, nor commented on the apparent discrepancy with the previous studies. Furthermore, Hümme et al. did not perform two-stage testing, consequently it is hard to determine if the behaviour actually changes with three stage loading compared to two stage, or if this is caused by another influencing factor.

The issue of multiple stage loading is clearly quite complex, especially as one move away from the two stage. While Holmen performed random loading and got only miner sums below one. Håverstad and Jensen however, reported on four stage compressive loading tests with LWA specimens. Their tests had a wide span of miner sums, yet a mean miner sum above one was found for all types of four stage loading. This is shown in Table 12.

Table 12: Four stage loading tests reported by Håverstad and Jensen[42]

Load History	Number of Specimens	Lower Miner Sum	Upper Miner Sum	Mean Miner Sum	Load Levels
	10	0.1687	30.58	5.39	S_{1max}=0.834, S_{2max}=0.785, S_{3max}=0.736, S_{4max}=0.683, S_{min}=0.196
	10	0.208	31.218	7.98	
	10	0.8741	22.83	6.19	

The sequence effect explanation by Baktheer and Chudoba[41] is unable to account for certain effects. These limitations of the model by Baktheer and Chudoba might explain some of the discrepancies in studies. Their model loses its validity for larger concrete structures, which tend to exhibit large amount of macroscopic redistribution. Consequently, an actual structure is expected to exhibit different behaviour than those seen in lab tests on small cylindrical specimens. If this redistribution also occur in specimens during multiple stage load test, it would explain some of the "chaotic" results. A summary of the investigations of stress range and reversals is given in Table 13.

Table 13: Investigations of multiple stage loading with respect to fatigue

Author	**Noticed effects**	**Note**	**Year/ Source**
Hilsdorf and Kesler	Stress range order and duration highly influence fatigue life	Flexural beams tested	1966[61]
Jinawath	Going from high to low stress level decreases fatigue life, indicating that the PM hypothesis is inaccurate	Two stage compressive loading	1974[6]
Tepfers et al.	High stress followed by low stress to tends decrease fatigue life	Two stage compressive loading	1977[82]
Holmen	Going from high to low stress level decreases fatigue life, indicating that the PM hypothesis is inaccurate	Two stage compressive loading	1979[21]
Holmen	Random loading seems to have shorten fatigue capacity compared to the P-M rule	Multiple stage loading	1979[21]
Hoff et al.	Going from high to low stress level decreases fatigue life, indicating that the PM hypothesis is inaccurate	Two stage compressive loading, lightweight aggregate	1984[84]
Håverstad and Jensen	Four stage loading has mean miner sums far above 1, though significant scatter	Four stage compressive loading, LWA	1986[42]
Oh	Decreasing subsequent loading decreases fatigue life	Four point bending, very large scatter in miner sums	1991[81]
Hordijk	High to low stress level increases fatigue life compared to the P-M rule	Tensile two stage loading	1992[80]
Hümme et al.	Decreasing stress level increased fatigue life in compression for three stage loading	Conflicting result of multiple loading in compression compared to others	2016[53]
Isojeh et al.	Proposed damage model with multiple amplitude compression tests based on ε_{II}	In agreement with general sequence effect in compression.	2017[29]
Baktheer and Chudoba	Energy consideration seems to explain sequence effects in compression	Two stage loading	2021[41]

3.11 Temperature

The effect of temperature change on concrete specimens is a well-known phenomenon and is not especially associated with fatigue. However, cyclic loading has been shown to induce severe temperature changes in the specimens in some cases.

One of the early studies of heat development due to cyclic loading was performed by Assimacopoulos et al.[46] in 1959. They monitored the surface temperature of cylindrical specimens during testing. Various maximum stress levels and five different minimum stress levels (10, 30, 50, 70 and 80%) were tested. Furthermore, the tests included two different loading frequencies: 500 cpm (8.3Hz) and 9000 cpm (150 Hz). The 500 cpm specimens displayed no significant increase in temperature. The tests from some of the specimens exposed to 9000cpm is included in Figure 55. Even though the specimens displayed some scatter in the results, both for fatigue life capacity and temperature development, Assimacopoulos et al.[46] found some clear trends. The temperature development was in some cases considerable. The greatest change in temperature occurred in the tests with the lowest minimum stress levels. This indicates that the temperature increase was associated with stress range as well as frequency. Interestingly, Assimacopoulos et al. were not able to find a change in the strength of the specimens despite considerable rise in temperature.

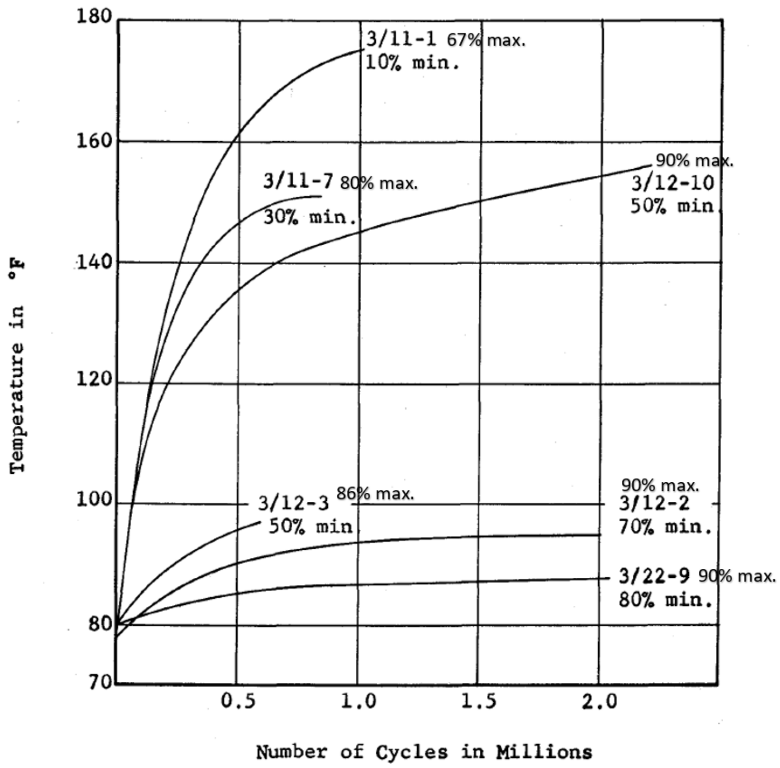


Figure 55: Temperature change in specimens during cyclic loading[46]

Whaley and Neville[87] published a paper in 1973 describing temperature measurements of concrete specimens exposed to cyclic loading. They tested only one frequency at 585 cpm (9.75Hz), which is quite close to the lower frequency used by Assimacopoulos et al.[46]. In contrast to Assimacopoulos et al., Whaley and

Neville found an increase in temperature. Furthermore, they found a proportional relationship between temperature increase and stress range. In addition, no influence on temperature was discovered when comparing different mean stresses. Whaley and Neville offer no indication of the potential damaging effect of temperature increase.

A more recent investigation of the temperature increase was performed by Elsmeier and Lohaus[88]. They used infrared temperature sensors as well as thermal imaging to monitor temperature and its distribution. Their specimens consisted of HSC cylinders with a height of 180 mm and diameter of 60 mm. They tested a wide range of maximum stress levels as well as frequencies between 1 and 10 Hz. They found that an increase in maximum temperature had only a slight influence on fatigue life with high stress level. High stress level caused failure before large heat accumulation occurred. For lower stress levels, the specimen endured more cycles. The lower stress level specimens had larger total temperature rise, but not higher per time increment. The specimens also exhibited a clear temperature gradient. The maximum temperature was found in the middle of the specimen and decreased towards the loading arrangement. Elsmeier and Lohaus believed that this temperature gradient could cause additional stresses within the specimens, thus explaining the observed reduction of fatigue life. Different frequencies were also found to be important for the temperature rise, where 1, 2, 5 and 10 Hz gave approximately 10, 20, 30 and 30°C increase, respectively.

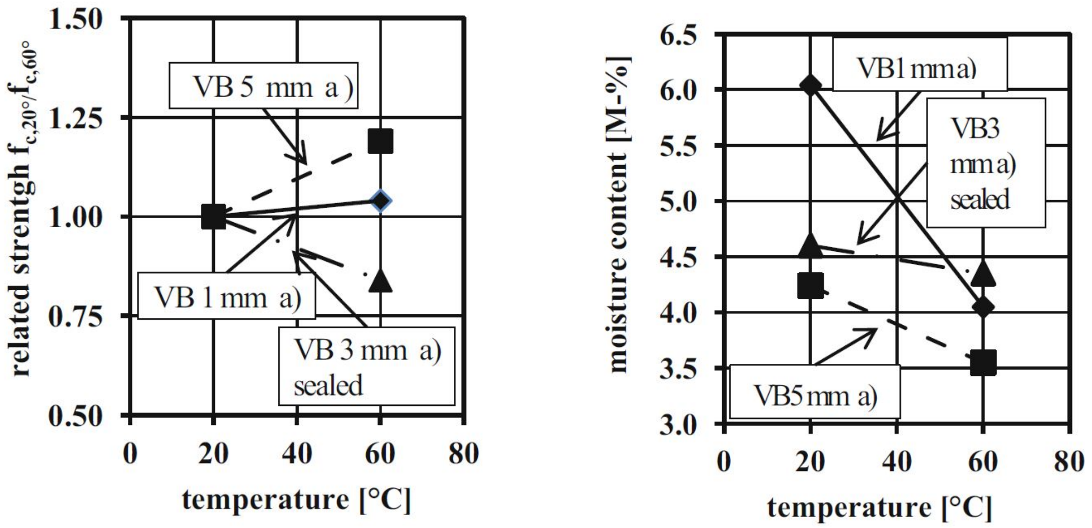
Temperature rise during fatigue testing have received an increasing amount of attention the last decade. This is reflected in the large amount of new articles and dissertations written investigating this topic. However, most of these articles are in German, requiring an extensive translation work for those not fluent in this language. However Market and Laschewski[89] published a paper in 2020 summarizing the findings within this subject. Different factors influencing the temperature development is summarized in Table 14 by Markert and Laschewski [89]. The interaction between different factors are complex, which highlights the difficulty of separating influencing factors on fatigue capacity.

Table 14: Summary of factors influencing the temperature development by Markert and Laschewski[89]

Influencing Factors	Conclusion	References
Frequency	Higher frequencies produce a higher heating effect	[46, 90–95]
Stress level	An increased related upper stress or stress amplitude leads to a faster temperature increase	[46, 90, 91, 95–97]
Humidity	A decreased concrete humidity leads to a slower heating and a lower maximum temperature	[90, 96, 98]
Compressive strength	A higher concrete compressive strength leads to faster heating and a higher temperature	[97]
Specimen size	A smaller diameter leads to a smaller surface to volume ratio (A/V) and thus to less heating	[99]
Maximum grain size	The smaller the largest grain, the stronger the specimen heating	[90, 91, 100, 101]

The relevance of temperature depends on whether it damages the specimens or alters the deformation behaviour during testing. It is possible that the temperature increase causes additional damage. However, studies have found conflicting results regarding this topic.

A recently published article by Otto et al.[23], treats the damaging effect of temperature in specimens exposed to high frequency. Previous tests with high frequency (10Hz) had been found to cause premature failure[23]. The temperature increase, which seemed to increase the drying of the specimens, was believed to be the cause of premature failure. During fatigue testing, specimens had achieved temperatures up to 60°C. The influence of the temperature increase on the monotonic compressive strength of the specimens was investigated. This was to provide an explanation for the observed fatigue behaviour. The results from the monotonic loading tests are shown in Figure 56a. Interestingly, the temperature increase is related to the moisture state. For the sealed specimen (VB 3mm), an increase in temperature decreases the compressive strength with about 20 %. Drying specimens gave an increase of 20% on the compressive strength. Hence, the influence of temperature depends much on its ability to increase dehydration of the specimen.



(a) Compressive strength at 20°C and 60°C relative to strength at 20 °C[23]

(b) Temperature and moisture content of specimens[23]

Figure 56: Investigation of temperature on monotonic compressive strength[23]

The issue of temperature is of most interest in testing and less in real applications. The desire to test efficiently, forces researchers to increase the frequency to reach high cycles in reasonable time. Otto et al.[23] try to remedy this using a frequency regime with stepwise frequency increase. A stepwise program extends fatigue life to some extent, but this is much less pronounced for the specimens with high moisture content. The temperature development at different frequencies was recorded as shown in Figure 57. The VB1, meaning the specimens with maximum aggregate size of 1mm, has the most aggressive temperature increase. This specimen had also significantly higher moisture content, as seen in Figure 56b. To reduce the moisture content some of the specimens were pre-tempered, which significantly altered their temperature development. Some of the differences in temperature development can also be attributed to the difference in aggregates. However, Otto et al. doesn't investigate this due to limited amount of specimens.

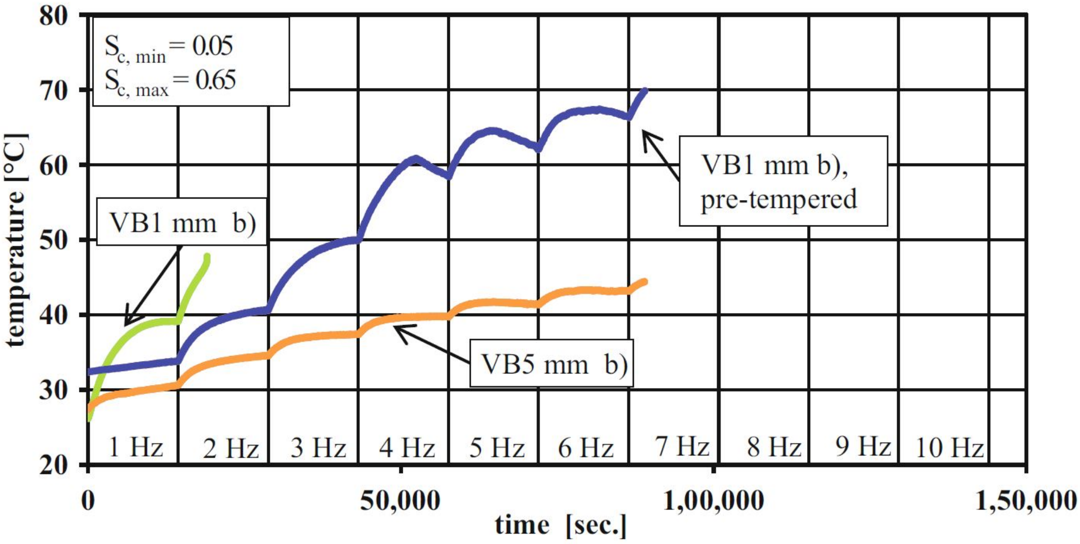


Figure 57: Temperature development at different frequencies[23]

Hümme et al.[53] found a distinct difference in ultimate strain as a result of temperature. A large temperature development increased the specimen length, thus reducing compressive strains at failure. However, the temperature accumulates during testing. Consequently, its maximum influence occur at the point of failure, but some influence was observed during the entire strain evolution.

The temperature is clearly a variable in need of attention when assessing fatigue tests. This is due to its interaction with several factors, which may alter the outcome of the tests. In addition to influencing fatigue capacity, temperature influences the strain behaviour. A summary of studies of temperature with respect to fatigue is given in Table 15.

Table 15: Investigations of temperature development with respect to fatigue

Author	**Noticed effects**	**Note**	**Year/ Source**
Assimacopoulos et al.	No change in fatigue capacity despite temperature increase & only higher frequencies yielded measurable temperature increases	Frequencies: 8.3 & 150Hz	1959[46]
Whaley and Neville	Lower frequency loading potentially yields large temperature increase. This depends on the stress range	Frequencies: 8.3Hz	1973[87]
Elsmeier and Lohaus	Sufficient temperature accumulation gives a decrease in fatigue capacity	Frequencies: 1-10Hz	2014[88]
Hümme et al.	Heating due to cyclic loading has a significant influence on fatigue capacity, and influences strain development	Frequencies: 1 & 10Hz	2016[53]
Otto et al.	The influence of temperature depends on the specimen dehydration	Frequencies: 1-10Hz	2018[23]

3.12 Time

Time complicates many investigations and forces researchers to alterate test parameters. This is needed to accommodate for available and practical test durations. Higher frequency is used to reduce the test durations. However, this may also alter the behaviour of concrete specimens, as discussed in section 3.3. Furthermore, properties of concrete changes with time due to creep, hydration etc. Consequently, it is of great interest to translate results from short time tests to large scale long duration cases. The effect of curing conditions and increased strength as concrete ages is a well-known phenomenon and needs to be taken into consideration. For those able to achieve a relatively short testing period, the aging effect might be neglected provided the concrete is of certain age. This arise from the fact that concrete strength gain decreases over time[20, p.304-306]. The fastest strength development occurs early in the life of the concrete. As seen from Figure 58 the increase of strength after three months is significantly reduced.

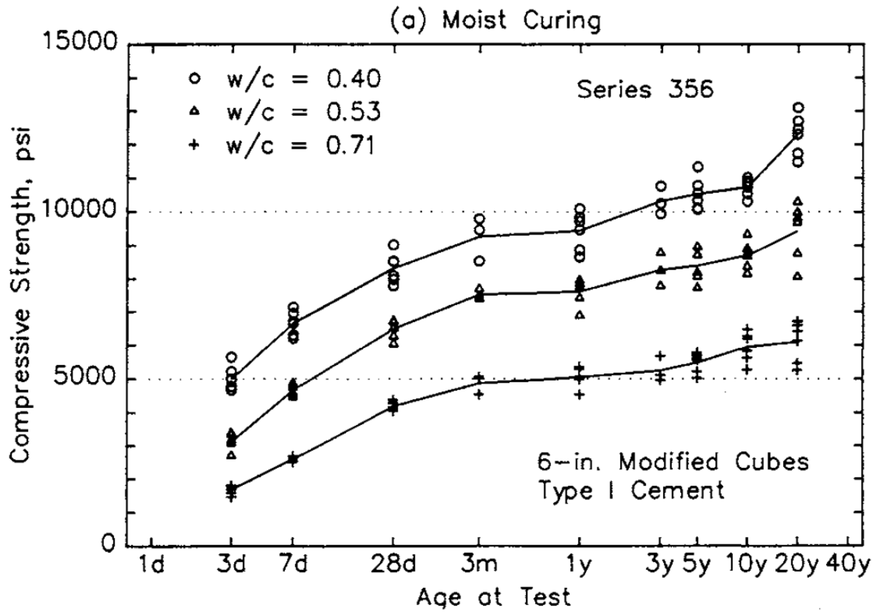


Figure 58: Strength development as a function of time[102]

Time may also cause development of creep. Creep is of interest for design considerations as it influences deformation, which is an indicator of fatigue life consumption. In general, creep is defined as the increasing strain development due to continuous loading[2]. Creep consists of two contributions: a recoverable part and an unrecoverable, as shown in Figure 59. The relationship between the creep phenomenon and the appliance of cyclic loading has received some attention, especially the computation of creep from cyclic loading. Intuitively, one might assume that the mean stress level of a cyclic load(S_m) is equivalent to a sustained load. However, this approach is inaccurate.

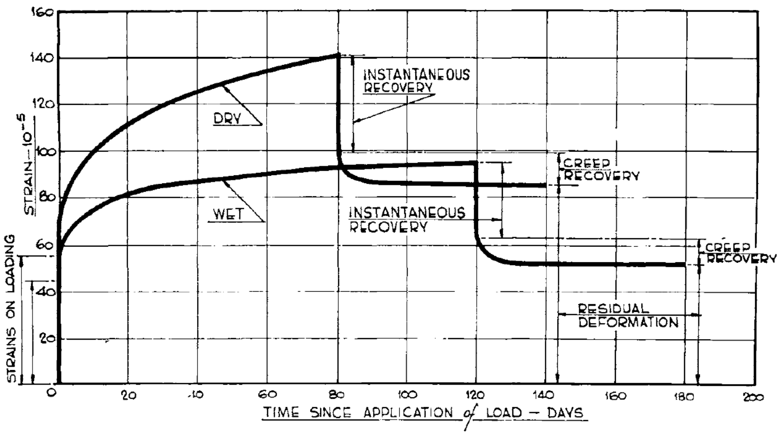


Figure 59: Creep development and recovery [103]

The issue of creep and its relation to cyclic loading has been investigated by Whaley and Neville[87]. They discussed the issue of cyclic creep under various loading compositions. They had three series of load schemes with different combinations, as shown in Table 16. For each combination, a minimum of three specimens were tested. In their definition of creep, all non-elastic deformation was considered as creep.

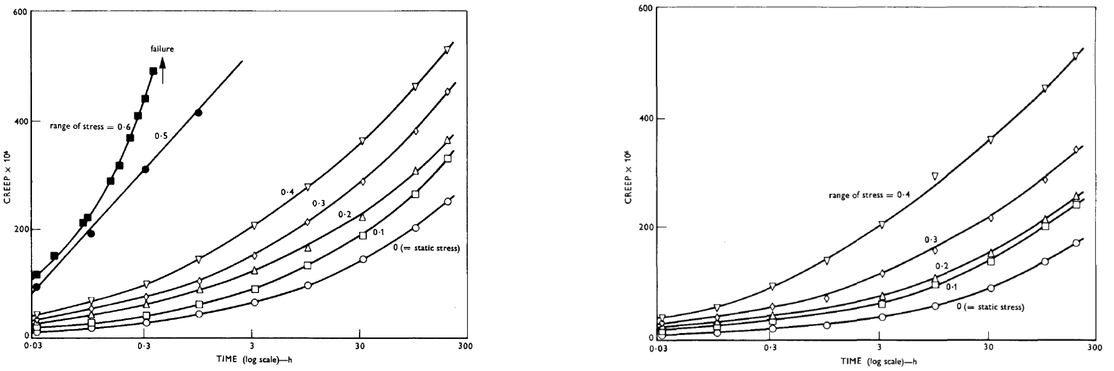
Table 16: Loading scheme by Whaley and Neville[87]

	Series 1		Series 2	Series 3
Combination	S_m=0.25	S_m=0.35	Δ=0.2	S_{min}=0.05
1	Δ=0.1	Δ=0.1	S_m=0.15	S_{max}=0.15
2	Δ=0.2	Δ=0.2	S_m=0.25	S_{max}=0.25
3	Δ=0.3	Δ=0.3	S_m=0.35	S_{max}=0.35
4	Δ=0.4	Δ=0.4	S_m=0.45	S_{max}=0.45
5	Δ=0.5	Δ=0.5	S_m=0.55	S_{max}=0.55
6	Δ=0.6	Δ=0.6		S_{max}=0.65

Whaley and Neville[87] found some interesting results in the fatigue behaviour. By changing the range of stress (Δ), the creep to increased uniformly for stress ranges below 0.4. For stress ranges above 0.4 the creep increased severely. This can be seen from Figure 60. Whaley and Neville considered the cyclic creep to have two constituents:

1. The stress range component: creep from the cyclic loading amplitude
2. The mean stress component: expected creep from a static loading at the mean stress S_m

The comparison of the two constituents can be seen in Figure 61. This comparison is based on the creep ratio, which is defined in Eq.6.



(a) $S_m = 0.35$ (b) $S_m = 0.25$

Figure 60: Influence of range of stress upon creep[87]

$$R_{creep} = \frac{\varepsilon_{meas} - \varepsilon_{S_m}}{\varepsilon_{S_m}} \quad (6)$$

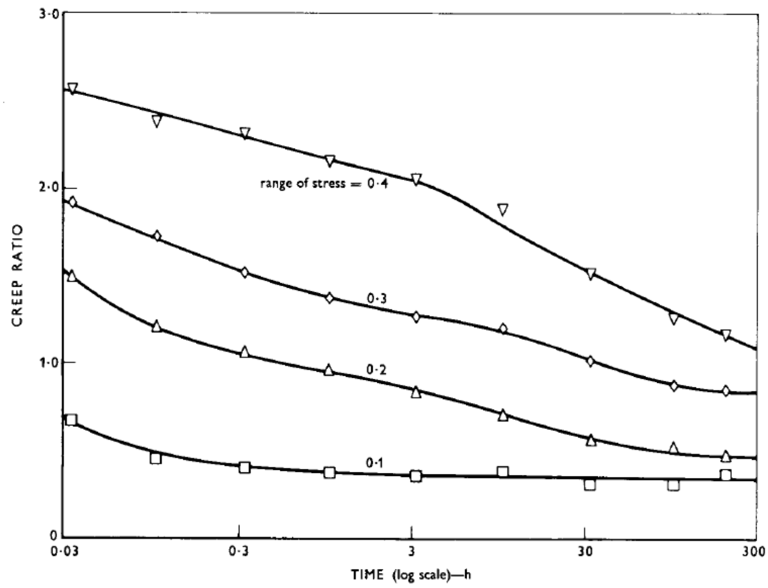


Figure 61: Ratio of range of stress component of the creep to the mean-stress component of creep[87]

The creep ratio decreased with time as shown in Figure 61. Hence, Whaley and Neville[87] concluded that creep due to cyclic loading, did not add to the creep from static loading. Instead, cyclic loading caused an acceleration of the creep. This conclusion has also been supported by Bažant and Kim[104].

The discussed studies [87, 104] indicate that cyclic loading causes different deformation behaviour over time. This was also found more recently by Hümme et al.[53]. They performed cylindrical compression tests with aging from 43 to 149 days, well above the age of maximum strength development. Their tests included frequencies of

1 Hz and 10 Hz, with test durations of approximately 28,5h and 1h, respectively. The average strain difference between the 1 Hz and 10 Hz specimens was 0.82‰. Some of this strain is caused by different temperatures. However, the difference in temperature was between 20-25 K. Thus, temperature differences only accounts for 0.20-0.25 ‰ of the strains, assuming a thermal coefficient of $1 * 10^{-5} \frac{1}{K}$[40]. The remnant strain difference is assumed to be caused by the difference in test durations. As a result, time effects causes considerable strains. A summary of the investigations of time with respect to fatigue is given in Table 17.

Table 17: Investigations of time with respect to fatigue

Author	**Noticed effects**	**Note**	**Year/ Source**
Whaley and Neville	The creep difference of cyclic and longtime static loading decreases in time		1973[87]
Bažant and Kim	The cyclic loading accelerates the creep compared to longtime loading		1992[104]
Hümme et al.	Significant amount of strain due to time effects verified by tests.		2016[53]

3.13 Multiaxial Stress States

The behaviour of concrete under multiaxial stress states is significantly less investigated than the uniaxial case. The multiaxial stress states can be divided into two groups, passive and active loading. The passive loading is a consequence of specimen restraints and the Poisson effect. An active loading is caused by an external load, restricting transverse strain. Both cases need thorough understanding as many constructions encounter both passive and active confinement. An active confinement pressure is found in prestressed structures exposed to excitation, while passive confinement is found where physical constraints are present. Confinement pressure is known to yield an increase in strength in static tests. The reason is that the failure mechanism changes from a brittle failure to a ductile crushing failure [72, p.295]. The effect of passive confinement for fatigue applications have been investigated by Desayi et al.[105] and Shah et al.[106].

Desayi et al.[105] and Shah et al.[106] studied the effect of cyclic loading on passively steel spiral confined concrete. The stress-strain relationship from fatigue tests was compared to the static loading curve. In general, the monotonic curve fitted well as an envelope curve for the cyclic loading. However, cyclic loading yielded displacements which exceeded the monotonic curve in certain conditions. Overall, the results suggest that passive confinement influences the static and cyclic strength similarly.

The increase in strains due to confinement is clearly shown by Buyukozturk and Tseng[107] in Figure 62. The figure traces the maximum points of the hysteresis curves and shows how increasing confinement pressure increases the failure strains.

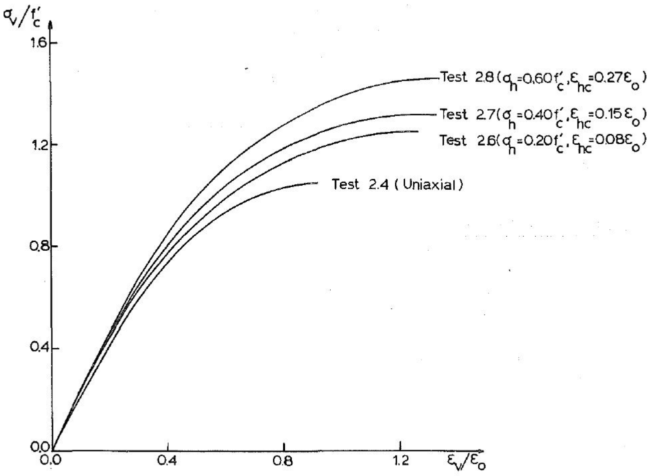


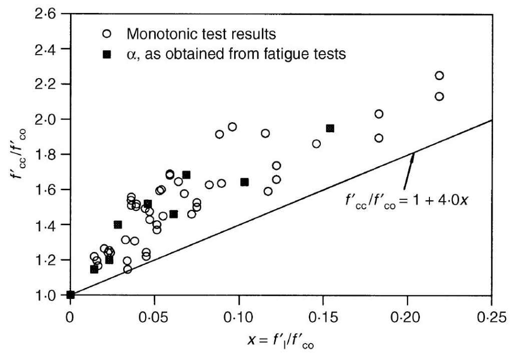
Figure 62: Envelope curves of unconfined specimens and confined specimens[107]

Hooi[108] studied the effect of passive confinement with respect to fatigue and its implementation in the linear S-N relationship. He performed fatigue and monotonically loading tests on concrete cylinders with different amounts of steel spirals as confining reinforcement. He altered the Aas-Jacobsen[37] formula (Eq.7) by replacing 1 with α. The term α accounts for the level of passive confinement reinforcement and is defined in Eq.8.

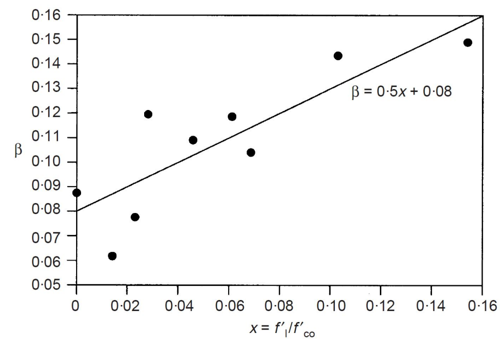
$$\frac{\sigma}{f_{co}} = 1 - \beta(1 - R) * log(N_f) \tag{7}$$

$$\alpha = \frac{f_{cc}}{f_{co}} = 1 + K_1 \frac{f_l}{f_{co}} \tag{8}$$

Hooi[108] showed that the α value for monotonic tests exhibited the same behaviour as the α value from fatigue tests. This is shown in Figure 63a. A strength increases with increasing amounts of reinforcement. However, increasing amounts of reinforcement also resulted in a steeper SN curve. This indicates a faster degradation of fatigue life per cycle. The change in slope, expressed through β, is does not reverse the benefits of the confinement reinforcement. The final regression lines from Hooi are shown in Figure 64 and the effect of confinement is clear. However, the difference diminishes with high number of cycles.



(a) α values for different reinforcement amounts



(b) β values for different reinforcement amounts

Figure 63: Change of factors in the S-N relationship with different confining reinforcement levels[108]

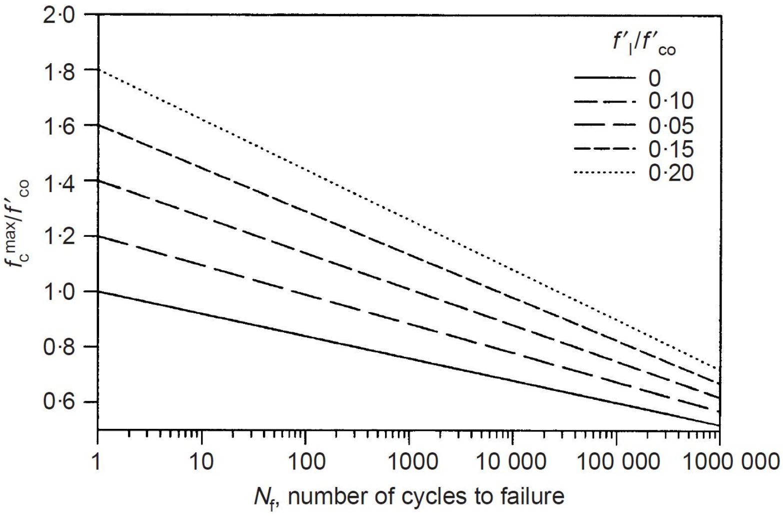


Figure 64: S-N curves proposed by Hooi[108]

Takhar et al.[109] studied the effect of active confining pressure. Their study showed an extension of fatigue life with confining pressure. However, this was only true at stress levels below $S_{max} < 0.9$, as seen in Figure 65. For the higher stress levels, no observable difference was found.

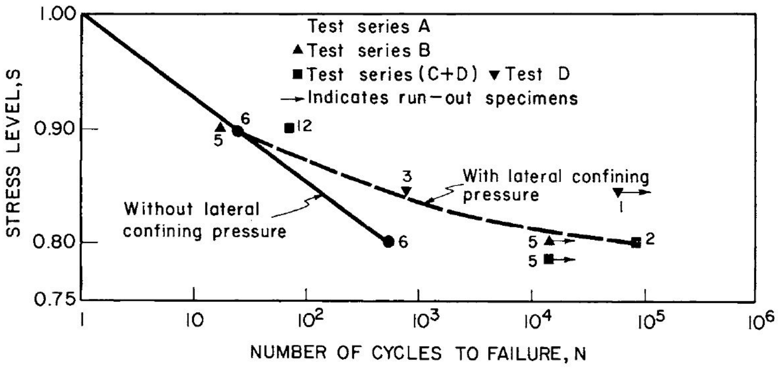


Figure 65: S-N relationships with and without active confining pressure by Takhar et al.[109]

A confining stress state seems to be exclusively beneficial for the fatigue strength. However, fatigue loading is only applied along one axis in the mentioned studies. Fatigue loading along more than one axis has been studied by Traina and Jeragh[110]. They applied a biaxial fatigue loading to concrete cubes and tested the following four types:

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 while σ_2 is constant at 6.9 MPa
4. σ_1 is cyclic while σ_2 is constant at 13.79 MPa

For all tests the σ_3 direction remained unloaded. Traina and Jeragh[110] found that setup 3 and 4 behaved similarly to the biaxial loading setup 1 and 2. In al cases, an increase in strength was observed compared to the uniaxial case. Traina and Jeragh found the increase to range from 33 to 45%. A higher confining stress level yielded a larger capacity. The results from Takhar et al.[109] found cyclic loading with confining stress (triaxial stress state) to have a larger benefit compared to the biaxial case from Traina and Jeragh[110]. The exact gain needs further investigation as the study by Takhar et al. contained a large amount of runouts. The triaxial fatigue capacities increased several times compared to the uniaxial case, even when runouts was considered as failures. Nevertheless, the studies have one major discrepancy in results. Traina and Jeragh found a beneficial effect of increasing the confining stress from 6.9 MPa to 13.8 MPa. Takhar et al. however, found the confining stress of 13.8 MPa to be less beneficial than 6.9 MPa. Both confining stresses yielded an increase compared to uniaxial case. The exact explanation for this discrepancy is hard to determine without a closer examination of the yielding in the specimens. However, the explanations from Hooi[108] may provide some insight. The failure of uniaxial compression is due to a tensile failure as a consequence of the transverse deformation of the specimens. The confining stress, changes this failure by reducing the stress around crack tips and slowing the microcrack formation. It also prevents transverse deformation. The hydrostatic stress from the confinement is generally beneficial. However it seems reasonable that a balance is required. At a certain point, it is therefore natural to assume that an increased confining compressive stress may have a degrading effect. The biaxial tests have the possibility of failing due to tension in the unloaded direction, while triaxial have less possibility for this. The different yielding mechanisms could explain the discrepancy.

Nelson et al.[111] performed biaxial cyclic loading tests on HSC. They found the biaxial stress state to be beneficial with S_{max} <0.75. An increase in the ratio of the two axial cyclic loads gave further strength increase. Surprisingly, the opposite trend was found for $S_{max} < 0.75$, where a decrease in strength was recorded with increasing load ratio. The biaxial tests by Traina and Jeragh [110] limited themselves to testing values $S_{max} > 0.75$. Hence, it is not possible to compare their results beyond the fact that both research groups are in agreement, when $S_{max} > 0.75$.

Taliercio and Gobbi [112] studied multiaxial stress states where the loading had a certain offset relative to each other. They conducted triaxial cyclic test on rectangular specimens with either the confining stress in phase with the axial load or in phase opposition. As expected from previously mentioned results the tests with confining stress in phase increased fatigue life compared to the specimens in phase opposition.

Multiaxial cyclic stress state includes several different stress states, making it difficult to draw an unambiguous conclusion. A constant surrounding stress with cyclic tension-compression applied examplifies this. Song et al.[113] exposed concrete prisms to cyclic axial tension-compression loading with an active confining pressure at various levels. As seen in Figure 66, the results showed a decrease in capacity with increasing confining pressure.

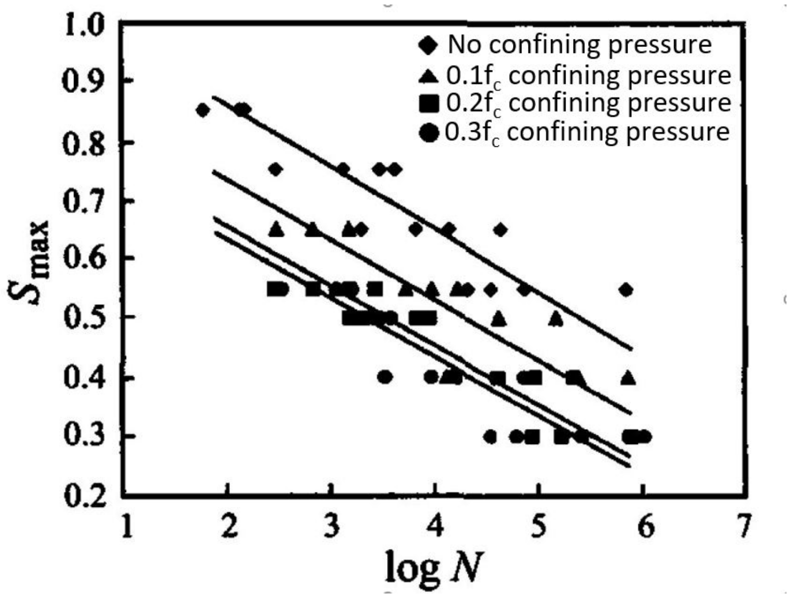


Figure 66: Results of tension compression loading in triaxial stress state by Song et al.[113]

Wang and Song[25] showed that a similar test setup with concrete prisms exposed to pure cyclic tension and confining pressure exhibited an increased fatigue life compared to a similar tension-compression specimen. Still, confining pressure is disadvantageous in both cases. In general, it seems to be beneficial with confining pressure if the specimen is exposed to cyclic compression. For pure tension, the confining pressure becomes a disadvantage. The combination of the two, tension-compression, yields a larger degradation rate and thereby reduce fatigue life.

The failure mechanism of multiaxial stress states is different from the uniaxially case shown in Section 2.2.1. For biaxial stress states the yielding of a cubic specimen tends to be a shear type of failure with a splitting of planes parallel to the free edges[24, 25]. This is shown in Figure 67. A summary of the research on multiaxial stress states with respect to fatigue is given in Table 18.

Figure 67: Yielding in biaxially loaded fatigue specimens[25]

Table 18: Investigations of multiaxial stress states with respect to fatigue

Investigation	**Author**	**Noticed effects**	**Note**	**Year/ Source**
Passive constant confining stress with uniaxial cyclic load	Desayi et al.	Similar benefit of confinement as for static application		1979[105]
Passive constant confining stress with uniaxial cyclic load	Shah et al.	Similar benefit of confinement as for static application		1983[106]
Passive constant confining stress with uniaxial cyclic load	Buyukozturk and Tseng	Similar benefit of confinement as for static application and significant difference in final strains compared to uniaxial stress state		1984[107]
Passive constant confining stress with uniaxial cyclic load	Hooi	Confinement is beneficial but the benefit decreases with increasing amount of cycles		2000[108]
Active constant confining stress with uniaxial cyclic load	Takhar et al.	Confining pressure is beneficial if S_{max} <0.9		1974[109]
Active constant confining stress along one axis with uniaxial cyclic load	Lü et al.	Biaxial compression is beneficial compared to uniaxial	Not discussed in text	2007[24]
Biaxial cyclic loading	Traina and Jeragh	Biaxial loading is beneficial compared to uniaxially		1982[110]
Biaxial cyclic loading	Nelson et al.	Biaxial cyclic loading is beneficial compared to uniaxially if $S_{max} > 0.75$		1988[111]
Triaxial cyclic loading	Taliercio and Gobbi	Multiaxial cyclic loading in phase yields far larger benefit than those out of phase		1996[112]
Active constant confining stress with uniaxial cyclic load	Song et al.	Confining pressure is disadvantageous with tension-compression cyclic loading		2005[113]
Active constant confining stress with uniaxial tension cyclic load	Wang and Song	Confining pressure is disadvantageous with pure tension cyclic loading		2011[25]

3.14 Reinforcement

Most concrete structures contain some sort of reinforcement and its effect on fatigue properties of concrete is therefore of great interest. For fatigue related yielding in concrete structures, there are primarily three places where this yielding occurs:

- In plain concrete
- In the steel
- In the bond between concrete

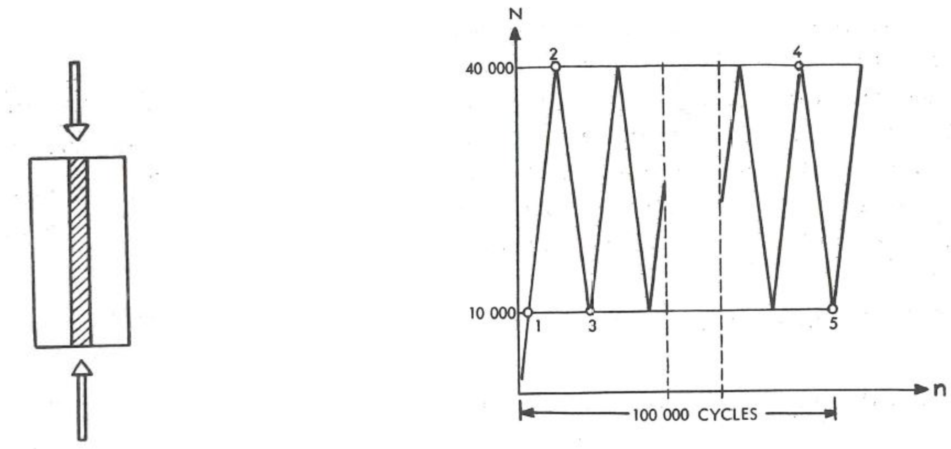
The fatigue of the reinforcement itself is not of interest in this thesis and no description of this yielding behaviour will be given. However, as it is desirable to extend fatigue life, the steel should be considered. According to Olsen[114], fatigue of shear reinforcement was the governing design factor on large parts of the Condeep platforms. Hence, extension of service life requires developments in several fields.

For a large number of fatigue tests involving reinforced concrete the final failure occurred in the steel[21, 115]. However, this is typically preceded by extensive cracking in the concrete. There are several reasons for this behaviour and the desire to design under-reinforced components with ductile behaviour is partly the culprit. This design highly utilizes the steel and thus fatigue failure of the steel is expected. Additional effects which cause steel failure have been identified when the concrete was design to fail first.

Aas-Jacobsen[37] performed fatigue tests of prisms, over-reinforced beams as well as over-reinforced columns. The specimens were designed to fail due to compression. However, some of them failed due to fatigue of the reinforcement. Aas-Jacobsen suggested that the strain behaviour of concrete under cyclic loading explained these findings. The gradual increase in plastic strains would cause an increase in the stress level of the steel resisting strain. The extent of this stress increase varies with different cross sections. Aas-Jacobsen created a numerical example to illustrate the potential effect of this redistribution. Based on analysis of his tests, he proposed the formula in Eq.9 for estimating the plastic strain due to fatigue loading. The specimen and its hypothetical loading is shown in Figure 68.

$$\varepsilon_f = \alpha * \frac{\sigma_{max}}{f_c \sigma_{max}} * \sqrt[4]{n} \tag{9}$$

The proposed formula in Eq.9 was utilized on a fictive reinforced prism[37]. If the concrete exhibited 20.6 MPa in the first cycle, this would be reduced to 15.7 MPa after 100 000 cycles. The steel would increase from 186 MPa to 235 MPa in the same period. As a result, concrete stress level is decreased by 24%, while the reinforcement stress level is increased with 26%. Both changes are considered to be substantial. The redistribution of stresses from the concrete to the steel during fatigue loading is shown in Figure 69. The increase in reinforcement stress level is a consequence of concrete deformation. Hence, the amplitude of the steel stresses do not change. The stresses are merely shifted to a higher mean level. Even though such a shift is detrimental for concrete, steel withstands it without much problem. This is because stress amplitude is the parameter of interest for steel[13]. The effect could



(a) Example specimen (b) Loading series

Figure 68: Example by Aas-Jacobsen to illustrate the effect of redistribution[37]

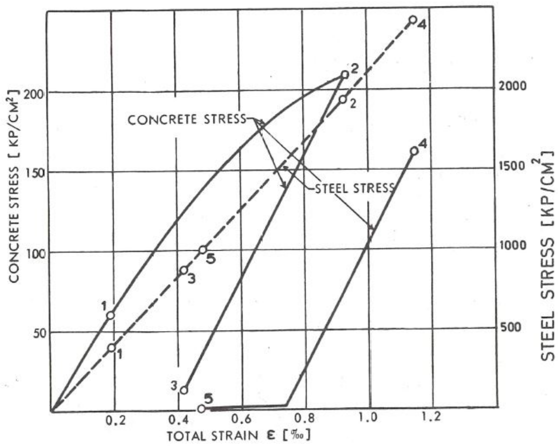


Figure 69: Change in stress at different cycles from example by Aas-Jacobsen [37]

potentially be a problem if steel utilization exceeds the ultimate limit state (ULS) requirements. Assuming that the steel has sufficient capacity for stress increase, this stress redistribution should cause an extension of the fatigue life of concrete. This could potentially allow fatigue life of concrete to surpass the fatigue capacity of the reinforcement.

Stress distribution from concrete to reinforcement was found to take place in the beams tested by Aas-Jacobsen[37]. This provided beneficial effects up to the point of compression reinforcement yielding, where the beams started to fail. It is typically prefered that the reinforcement yields, allowing the structure to exhibit large ductile strains upon failure. This is complicated by fatigue design of both concrete and reinforcement. A yielding of plain concrete due to fatigue, is usually a gradual and ductile failure. In contrast, the fatigue yielding of reinforcement is abrupt with little deformation to indicate failure. This issue need careful considerations during design. Aas-Jacobsen used his numerical example and applied the method to the tested beams and columns in order to calculate the redistribution of forces. The exact computational method will not be presented here, but follows well known principles regarding determination of internal stresses and corresponding strains. The numerical method showed a relatively good fit with measured values, as indicated in Figure 70. The internal stresses for different number of cycles result in a decrease of concrete stress and an increase in steel stress. This is demonstrated in Figure 71. The lower stress level in the top steel at M_{min} goes from approximately 0.4 to 0.8 of yield stress at n=1 and n=100 000, respectively. This is demonstrated in Figure 71. Interestingly, the upper stress level exceeds the yield strength. Aas-Jacobsen[37] found, when examined the yielding, that the compression reinforcement had buckled. This buckling is perceived to be caused by an increase in steel stress due to redistribution of stress.

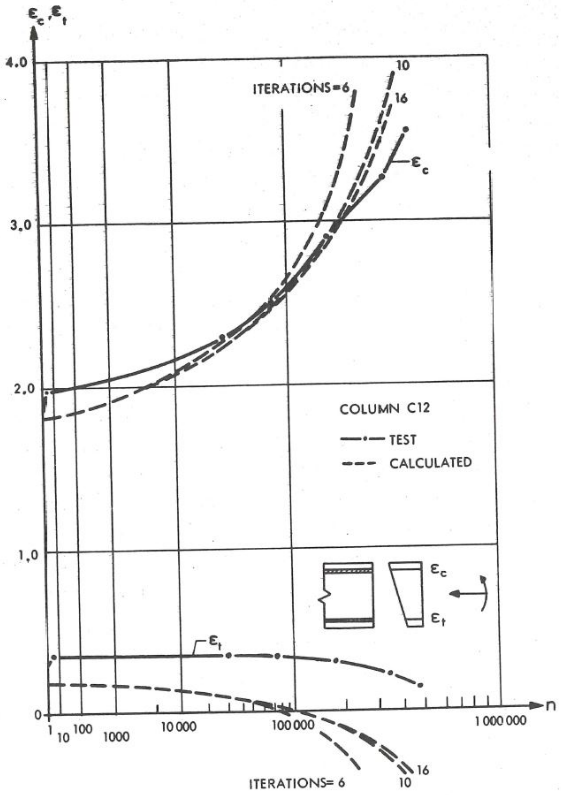


Figure 70: Comparison of the computed and measured strains on a column[37]

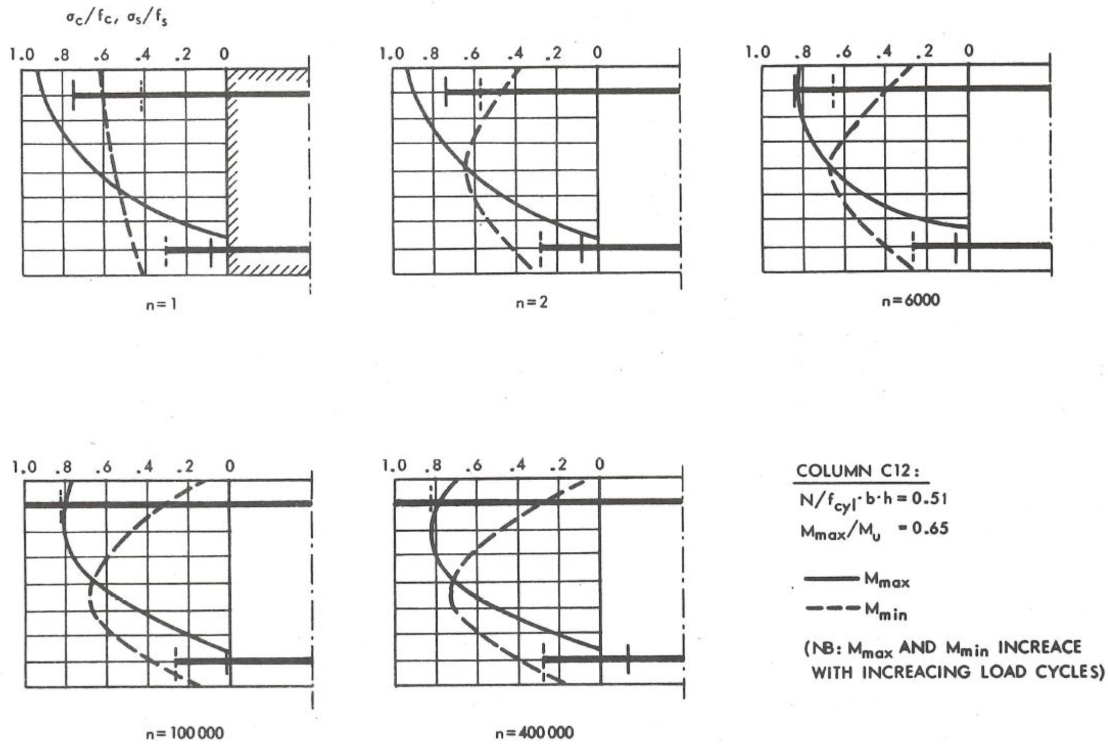


Figure 71: Redistribution of forces within the section for different cycles[37]

Stress redistribution might also be an issue for the bond between reinforcement and concrete. This issue is not addressed by Aas-Jacobsen, but others have investigated this. Balázs[116] studied bond fatigue by testing bars embedded in concrete and measuring the amount of slip during cyclic loading. In general, the deformation of bond slippage was similar to the expected fatigue deformation of concrete. Bond deterioration exhibited three stage strain development with the same characteristics as fatigue of concrete. This can be observed in Figure 72.

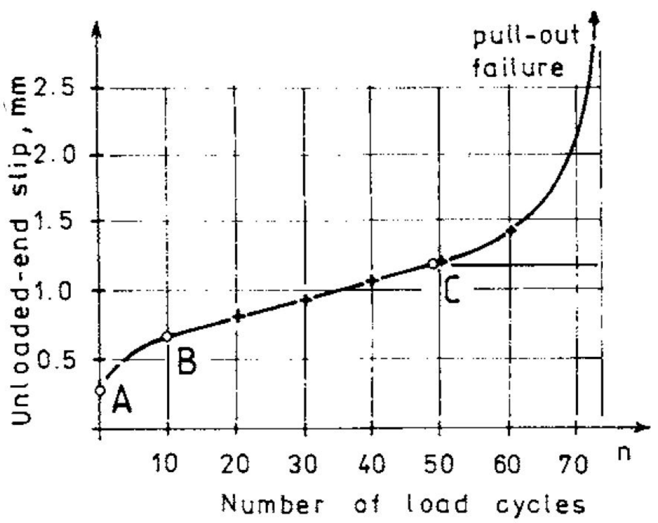


Figure 72: Bond slippage behaviour according to Balázs[116]

According to Balázs[116], cyclic degradation of bond is caused by the progressive microcracking and microcrushing in front of the protruding lugs on the reinforcement. Interestingly, Balázs found a large increase in slip per cycle when specimens were exposed to reversed loading. Reversed loading resulted in approximately four times higher slip compared to cyclic loading without a change in sign.

Bond strength is influenced by several factors, including concrete strength, bar diameter, concrete cover and confining effects[116]. Rehm and Elighausen[117] investigated fatigue of bond. They found no effect of concrete strength, nor bar diameter, when fatigue bond strength was expressed as a ratio of static bond strength. A more recent investigation by Sun et al.[118] found the following to be important:

- Stirrups or other types of confinement are beneficial
- Bond length (no comparison to the static effect)
- Load parameters influencing fatigue of plain concrete have a similar influence on fatigue of bond

If bond fatigue becomes an issue for a structure will vary. However, tests by Muhlenbruch[119] indicate that a large cyclic stress is required for bond failure to occur. Figure 73 displays his results from fatigue tests on rectangular concrete specimens with 16mm diameter bar.

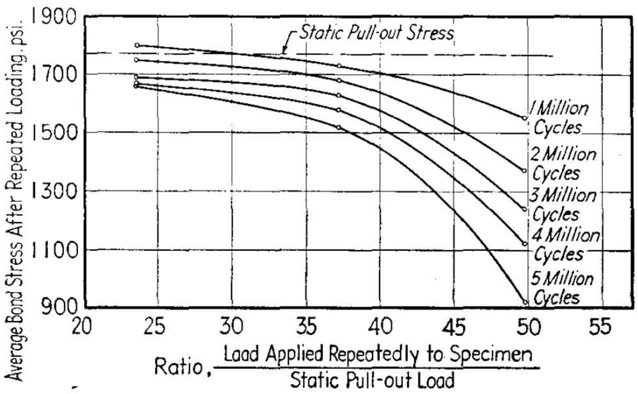
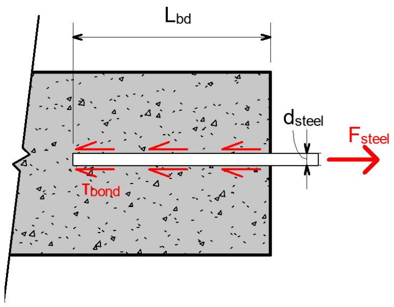


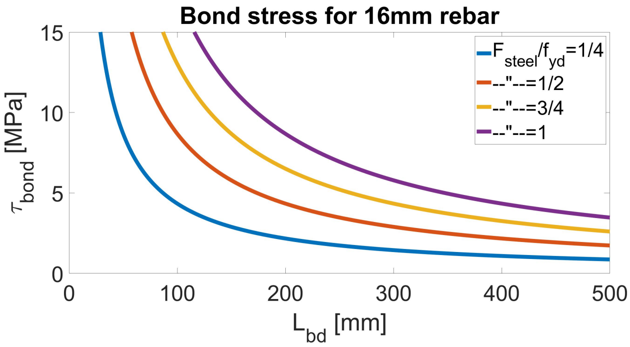
Figure 73: Results of fatigue test by Muhlenbruch [119]

The expression for bond stress is shown in Eq.10. This equation expresses anchor stress as a function of force, anchor length and bar diameter. Figure 74 illustrate the bond stress for different levels of steel utilization. The amount of anchor length needed to have a stress level below 900 psi(6.2MPa), even at a steel force equal to yielding, is still less than 30cm. This might explain why the Eurocode assumes bond failure to be irrelevant given that the normal rules for reinforcement is in compliance. The issue of bond fatigue is therefore typically found in more special construction cases. An example of this is the case of Saito et al.[120] where the connection between wind turbine towers and the foundations failed prematurely due to bond fatigue. A summary of studies concerning concrete fatigue in relation to reinforcement is given in Table 19.

$$\tau_{bond} = \frac{F_{steel}}{\pi * d_{steel} * L_{bd}} \tag{10}$$



(a) Illustration for parameters from Eq.10



(b) Different bond stresses for 16mm B500NC rebar exposed to different fractions of yielding force

Figure 74: Bond stress example

Table 19: Investigations of reinforcement with respect to fatigue

Author	**Noticed effects**	**Note**	**Year/ Source**
Muhlenbruch	Early investigation of bond fatigue, with proposed capacity curves for bond fatigue		1945[119]
Aas-Jacobsen	Cyclic loading may substantially increase the stress in the steel and relieve the concrete		1970[37]
Rehm and Elighausen	Bar diameter and concrete strength do not influence bond fatigue if strength is taken as a ratio of static strength		1979[117]
Balázs	Bond fatigue strain exhibits similar behaviour as concrete		1992[116]
Sun et al.	Factors influencing concrete fatigue have similar effect on bond fatigue		2017[118]
Saito et al.	Windtower foundations failed prematurely due to bond fatigue		2020[120]

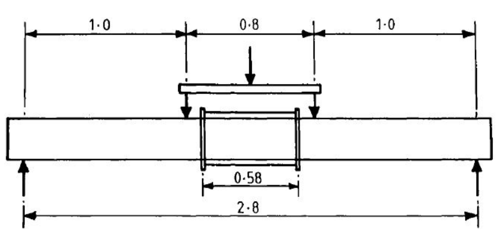
3.15 Sea Water

The issue of concrete durability has received a significant amount of attention. One of the major challenges in concrete durability relates to degradation caused by sea water. The degrading effect of sea water is caused both by the mechanical action of waves and induction of chemical reactions in concrete. For reinforced concrete, steel corrosion and subsequent cracking of concrete due to corrosion expansion of the steel are probably the primary concern. However, steel corrosion will not be discussed in this thesis as the main focus is effects on concrete itself. Furthermore, mechanical degradation of concrete due to waves is hard to generalize as it depends on several factors. The chemical reactions of concrete exposed to sea water are much more consistent, and only negligible variations occur. The chemical reaction between concrete and sea water is shown in Eq.11[20, p.518].

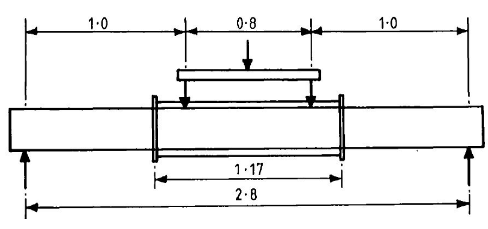
$$MgSO_4 + Ca(OH)_2 \rightarrow CaSO_4 + Mg(OH)_2 \tag{11}$$

Magnesium hydroxide $Mg(OH)_2$ forms a protective layer at the surface of the concrete, thus preventing further reaction. However, sea water erodes this layer. Hence, the process restarts and concrete is further degraded. Sea water may also cause an effect know as salt weathering which arises in structures periodically exposed to sea water[20, p.518]. When sea water evaporates, salt crystals remain in the concrete. When these crystals are exposed to water, they expand and cause stresses inside the concrete. Based on the degrading effects of sea water and moisture, discussed in Section 3.5, a decrease in fatigue life for specimens in sea water is expected.

Several studies have identified the expected degrading effect of water. Nevertheless, some have found certain beneficial effects. The study by Arthur et al.[44] found the effect of sea water to be somewhat conflicting. In their experiments reinforced concrete beams were exposed to unidirectional and reversed bending. They used a test setup where plastic water jackets enclosed the middle of the beams. Consequently, beams exposed to sea water at the critical part of the section could be compared to unexposed beams. Furthermore, the water jackets only confined the beams to such an extent that the water pressure could be neglected. Arthur et al.[44] made two versions of this setup, where the only difference was the length of the water jacket. This is illustrated in Figure 75.



(a) Short jacket



(b) Long jacket

Figure 75: Test setup for beams in sea water by Arthur et al. [44]

Arthur et al.[44] found that sea water under certain conditions could extend the fatigue life of beams. For the unidirectional bending tests submerged in sea water with low frequency loading, an increase in fatigue life was found compared to the specimens in air. The low frequency was set at 0.17 Hz and was designed to approximate the frequency of large beams in the North Sea. The beams tested in air mainly cracked in the maximum bending zone of the beam, as expected. Most beams in sea water cracked outside of this zone. In addition, the short jacket beams also exhibited leakage of sea water outside the jacketed zone. Arthur et al.[44] believed that this water followed an internal path to the cracks. For the long-jacketed specimens, failure occurred in the reinforcement within the jacketed zone. However, these specimens displayed increased concrete fatigue resistance compared to air specimens. A deposit in the cracks of the beams exposed to sea water was seen to accumulate during the first ten days. This deposit consisted of calcium carbonate($CaCO_3$) and magnesium hydroxide($Mg(OH)_2$). The deposits seemed to slow down the deformation rate by the effect of crack blocking. Arthur et al.[44] suggest that the crack blocking prevents the beam from returning to its undeformed shape upon unloading. Hence, the applied stress range is reduced. The benefit of this effect can be seen in Figure 76, where the specimens with low frequency in sea water exhibit longer fatigue life than equivalent air samples. In addition, the low frequency specimens exhibit a strength increase compared to the high frequency.

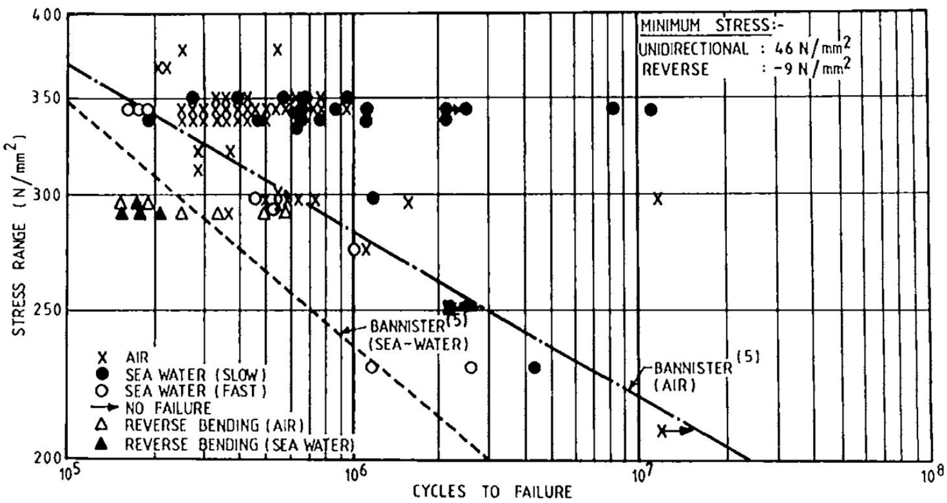


Figure 76: Results of fatigue beam tests by Arthur et al.[44]

The beneficial effects of sea water depends on frequency, which may be the reason why the crack blocking effect is useless in design. Arthur et al.[44] did not test the effect of changing the frequency after a deposit has accumulated. Hence, it is only possible to speculate on this effect. In some of the low frequency tests, the deposit unblocked itself causing a major spike in deformation. Gradually, new deposits started forming. The reason for the unblocking is not given by the authors, but it seems reasonable that mechanical interactions from the surroundings could be sufficient to remove such deposits. In the case of reversed bending, the number of specimens was limited and statistical significant conclusion cannot be made. However, Arthur et al. found no increase in fatigue lifespan for these specimens, despite the formation of deposits. The authors assumed that further studies might show that crack blocking would leave the stress range unchanged. This is due to the presence of crack blocking both in the top and bottom of the beam. Furthermore, this would cause the steel at top and bottom to exhibit larger stresses than before with the same loading.

Paterson[121] has performed similar tests as Arthur et al.[44]. He also found formation of deposits cracks, although specimens in sea water exhibited shorter fatigue life than in air. Paterson[121] showed that the failure happened in the steel reinforcement. Hence, the variation in reinforcement size and placement might also influence the benefits of crack deposits. Paterson however, found an increasing stiffening effect on the beams in sea water and attributed this to crack deposits. This suggests that some beneficial effects of sea water were present, but did not outweigh the degrading effect of water/moisture present. A summary of the studies of sea water is given in Table 20.

Table 20: Investigations of effect of sea water with respect to fatigue

Author	**Noticed effects**	**Note**	**Year/ Source**
Paterson	Beneficial effects of sea water does not outweigh the degrading effects		1980[121]
Arthur et al.	Sea water may increase fatigue capacity		1982[44]
Neville	Summarizes general findings of sea water with respect to concrete		2011[20]

4 Fatigue Design

The purpose of this section is to introduce design rules of fatigue, and some of the improvements suggested by researchers in this field. This will highlight some of the challenges of fatigue design and indicate how proposed models offer some insights into the mechanism behind the effects presented in Section 3.

4.1 Current Design Rules

This thesis has described several factors influencing concrete fatigue, thus highlighting the need for design rules. Although the CEB-FIP report[12] from 1988 found no collapses which could be attributed to concrete fatigue, the problem was still considered relevant. This was because damage and deformations caused by concrete fatigue could be a costly affair, and such mechanisms were believed to contribute to the degradation of several structures.

The Eurocodes are the main provider of design rules, although others do exist. The treatment of fatigue in the Eurocodes has been simplified and subjected to quite conservative considerations in order to ensure safety. The Eurocode mainly bases its treatment of fatigue on SN curves. These curves are generated by regression curves from data acquired by testing of plain concrete cubes and cylinders. The method provides a reasonable and safe approximation, but tends to only account for some of the factors influencing fatigue performance.

The Eurocode concerning concrete in general, NS-EN 1992-1-1[40], has a set of very simplified rules to account for fatigue. These rules are based on the regression lines which can be found in NS-EN 1992-1-2[35], and typically achieve a lower utilization than NS-EN 1992-1-2. According to Section 6.8.1 in the Eurocode[40], concrete and reinforcement should be considered separately for fatigue.

The verification of reinforcement uses SN diagrams and the P-M rule. The Eurocode[40] adds additional stress range to account for bond behaviour of various reinforcement types. The reinforcement is verified for sufficient capacity within its intended service life. This verification also decides the remnant fatigue life of the reinforcement. Concrete on the other hand, is simply checked for its ability to withstand a certain number of cycles, usually 10^6 cycles. The formula in Eq.12 from NS-EN 1992-1-1 is used.

$$E_{cd,max,equ} + 0.43 * \sqrt{1 - R_{equ}} \leq 1 \tag{12}$$

NS-EN 1992-1-2[35] provides an option which yield a larger capacity for concrete withstanding less than 10^6 cycles. This is based on the same formula as Eq.12, but replaces 0.43 with $log(N)/14$. This results in the formula given in Eq.13.

$$N = 10^{14 * \frac{1 - E_{cd,max}}{\sqrt{1 - R}}} \tag{13}$$

Eq.13 has the following input parameters:

- N : Number of endurable cycles
- $E_{cd,max}$: Maximum relative stress level, relative to a reference fatigue strength
- R : Stress level ratio
- $f_{cd,fat}$: Reference fatigue strength

As a result, the Eurocode only accounts for a small amount of fatigue effects. The fatigue reference strength ($f_{cd,fat}$) is supposed to take time and other effects into account, but accomplishes this in a generalized and unspecific manner.

Another source of design rules is provided by FIB (Fédération internationale du béton) through the model codes. A comparison of NS-EN 1992-1-2[35] and Model Code 2010[34] reveals some differences. The most current published model code, Model Code 2010[34], contains an updated fatigue section based on Lohaus et al.[122]. Their contribution was a model on fatigue which included ultra high strength concrete(UHPC), that is concrete with compressive strength above 100 MPa. However, their contribution was not limited to UHPC. They have also performed numerous test on normal and high strength concrete, thus increasing the amount of available data on these as well. The updated SN curves account for fatigue using the same parameters as the Eurocode. Hence, the Model Code 2010 and the Eurocode only yield slightly different results, as seen in Figure 77.

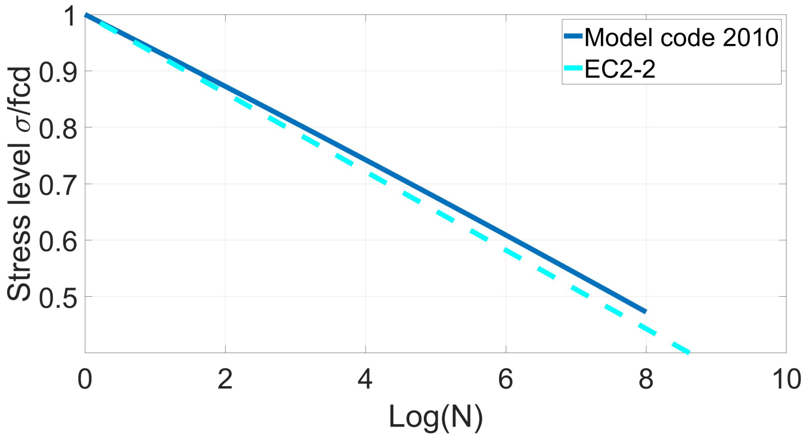


Figure 77: Comparison of SN-curves from Eurocode 2[35] and Model code 2010[34]

Both the Eurocode[35] and Model Code 2010[34] utilize the P-M rule to treat variable amplitude loading. As discussed in Section 3.9, the method is not consistently applicable to concrete. However, it is still widely used. This is due to lack of better options, as stated by several studies, including the Rilem report from committee 36-RDL[14]. This indicates a need of better methods to account for fatigue damage. Several researchers have proposed methods for fatigue estimation with varying general applicability.

The treatment of variable amplitude loading and the sequence effect display the largest "gap" between real life tests and design methods. The other effects influencing fatigue, could potentially be accounted for using certain coefficients. In contrast, the sequence effect cannot be accounted for in a satisfactory manner using coefficients.

There have been several attempts to procure a method for the damage development of concrete under varying amplitude loading. Discussed in Section 3.9, Hilsdorf and Kesler[61] proposed a model in an attempt to account for the sequence effect. However, extensive research is needed to generate sufficient data. It is also important to note that the complexity of the sequence effect make it difficult to determine beneficial loading order, as it changes based on action type. Several researchers have concluded that the solution must lie in an analytical method, and not an empirical method, due to the vast loading possibilities.

4.2 Nonlinear Damage Approaches

The curves for deformation, acoustic emission and ultrasonic pulse velocity show a three stage trend. This was described in Section 2.2 and suggests a nonlinear damage accumulation in concrete. Hence, most attempts to find a substitute for the P-M rule use a nonlinear damage accumulation. Holmen[21] attempted to find appropriate methods for cumulative fatigue damage by looking at the more extensive research for steel. He found several methods, but these shared the same flaw as the model by Hilsdorf and Kesler[61]. They required extensive testing or had other practical limitations. Baktheer et al.[86] tried to solve the issue by modifying the P-M rule in order to include the nonlinear damage development and the sequence effect. The method is based on a numerical model by Alliche[123], which utilizes damage mechanics to describe the accumulation of damage. A derivation of this three dimensional model will not be given here as it would require a thorough description of continuum mechanics. In addition, the model is merely a tool to generate sufficient data to decide parameters of their enhanced P-M rule. The model yields quite different results from a linear P-M rule, as can be seen from Figure 78. However, it corresponds well with two stage loading tests.

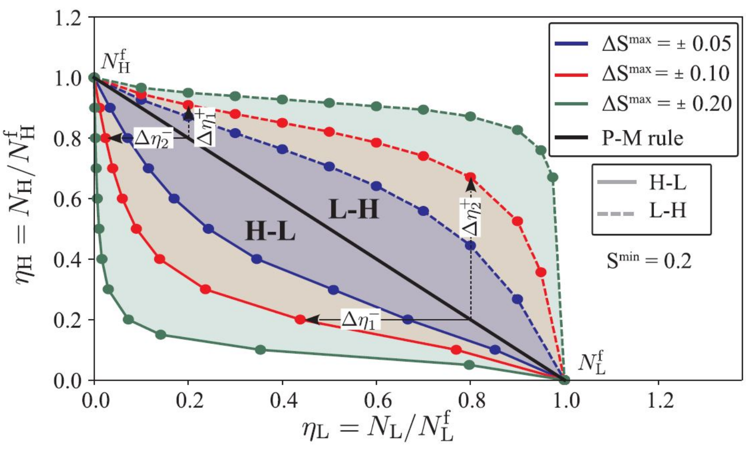


Figure 78: Model by Alliche[123] compared to the P-M rule for two stage loading[86]

The model by Baktheer et al.[86] is used to approximate the results from the single amplitude tests by Schneider et al.[124], as well as the two stage loading tests by Holmen[21]. The final model shows a relatively good fit with the test results as seen in Figure 79.

The strain behaviour is the key benefit of the idealized model from Baktheer et al.[86].

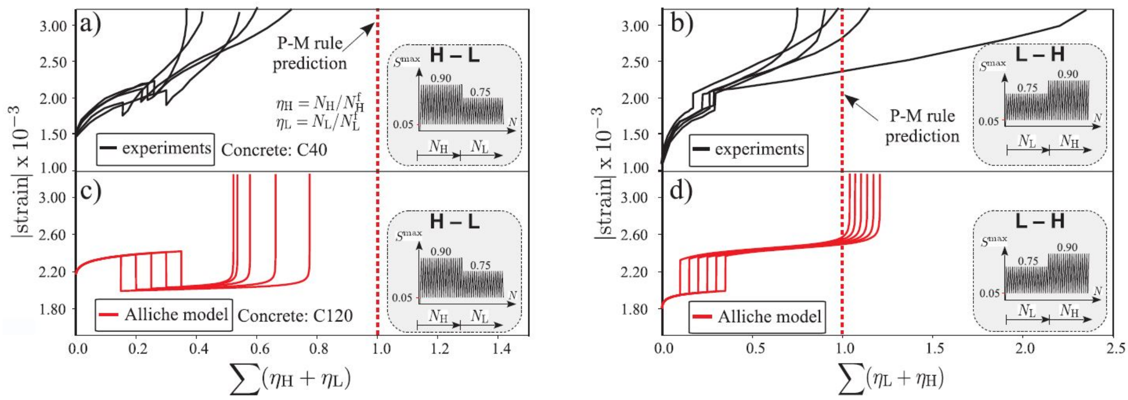


Figure 79: Comparison of model used by Baktheer et al.[86] based on Alliche[123] and test results by Holmen[21]

The model predicts the fatigue life from a two stage loading to follow the strain-damage curves of the loads. The shift between the loads corresponds a shift along the abscissa (damage development), matching the strain level of the subsequent loading curve. This is shown in Figure 80. Baktheer et al.[86] used the simple behaviour found for the sequence effect to propose an enhanced damage accumulation rule which was still much based on the P-M rule. The proposed rule adds a term to the P-M rule, as shown in Eq.14.

$$\eta = \sum_{i=1}^{n} \eta_i + \sum_{i=1}^{n-1} \Delta\eta_i \tag{14}$$

The equation represents fatigue failure at $\eta = 1$, similar to the P-M rule. The first term $\eta_i = \frac{N_i}{N_{if}}$ is unchanged from the P-M rule. The second term accounts for the sequence effect and the non linearity of damage accumulation. The term takes several factors into consideration, as can be seen in Eq.15.

$$\Delta\eta_i = R(\bar{S}_i, \Delta S_i^{max}, \Delta S_i^{min}, \tilde{\eta}_i) \tag{15}$$

Coefficients of $\Delta\eta_i$ were determined by data simulations and certain approximations. The result was a damage accumulation rule which fits well with the results of Alliche's model. This is as expected as the rule has been tuned to approximate this. Regardless, the enhanced P-M rule offers a simple way to check accumulated damage due to fatigue. However, the model by Alliche and the enhanced P-M rule needs further validation.

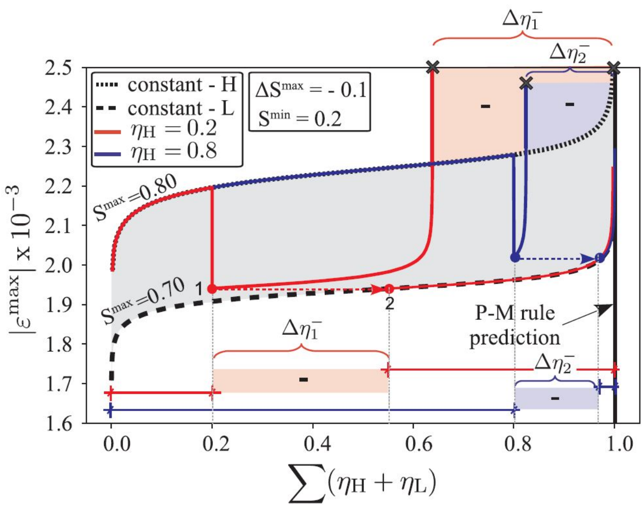


Figure 80: Strain and damage development modeled by Baktheer et al.[86]

Baktheer et al.[86] assumed that the nonlinear damage curves for different loadings can be summed. This have been assumed for several decades, yet its implementation has not been achieved. In 1986, Lenschow[125] evaluated the Norwegian rules for the fatigue design and briefly discussed the P-M rule. At that time, it was acknowledged that the strains could be a good damage indicator. Furthermore, the damage propagation of multiple stage loading was believed to follow the strain curves. A shift in load resulted in a shift to the strain curve of the subsequent loading at the accumulated value of ε. A visualization of this concept is shown in Figure 81. Going from a low to high stress would follow the course 0-2-1-3-4. The opposite follows 0-1-3-5-6. The damage accumulation rule shown by Lenschow[125] needed large systematic testing in order to determine the deformation curves. If the method should be feasible, the different factors influencing strains, especially strains at failure, would probably need to be subjected to conservative simplifications. Lenschow[125] proposed to lower the accepted value of the P-M rule from unity to 0.6 to account for sequence effects. The reason was that stochastic variable compression tests performed by Holmen [21] exclusively had mean Miner sums below one.

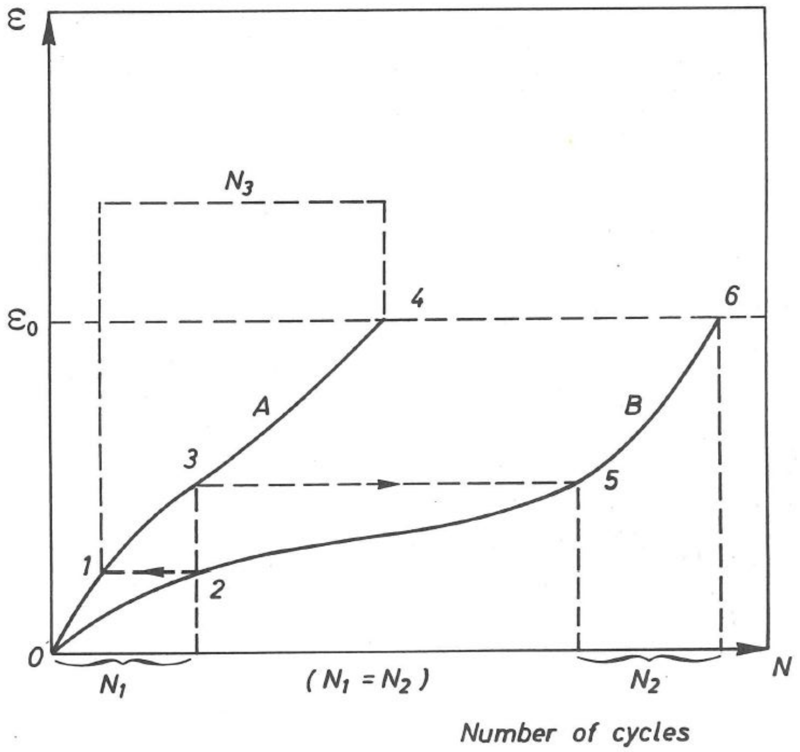


Figure 81: Deformation due to multiple stage fatigue loading[125]

The issue with damage accumulation design has been, and still is, the lack of experimental tests in order to verify analytical models. A purely experimental verification of load combinations requires far too extensive efforts.

4.3 Deformation Design

This thesis has mainly focused on the ability of concrete to withstand fatigue loading. For practical applications, it might be equally relevant to study the deformation to ensure that the structure remains suitable for its intended applications.

Model Code 2010[34] offers a simplified suggestion to approximate deformation from cyclic loading. The Model Code suggests the formula shown in Eq.16[34].

$$a_n = a_1[1.5 - 0.5e^{-0.03n^{0.25}}] \tag{16}$$

where a_n is the deflection after n cycles and a_1 is the deflection in the first cycle due to the maximum load.

Eq.16 considers a small number of variables. Hence, it is expected to yield conservative results due to the complex nature of fatigue. The estimation of deflections and strains is a complicated matter. The strain development tends to follow the three phase S-curve, as described in Section 2.2. The duration of each phase changes with the concrete strength. Furthermore, the duration of the different stages seems to change when a specimen endures more cycles due to change in some of the factors discussed in Section 3. The increased fatigue life seems to result in an extension of phase two, i.e. the stable strain propagation phase[18]. The final strains are also influenced by various factors. Hümme et al.[53] compared the final mean strains of fatigue tests to their respective monotonic failure strains. These exhibited quite similar failure strains as seen in Figure 82. Interestingly, all mean values were below the descending branch of their respective stress strain curves as given by the Model Code 90. The same tendency of final fatigue and static strain was found by Petkovic[17] as well. She found that the fatigue strains of HSC were the same or slightly higher than the static case. The referenced fatigue tests used quite high stress levels with relatively short test periods. For lower stress levels, longer time will pass before failure and creep will have a larger influence.

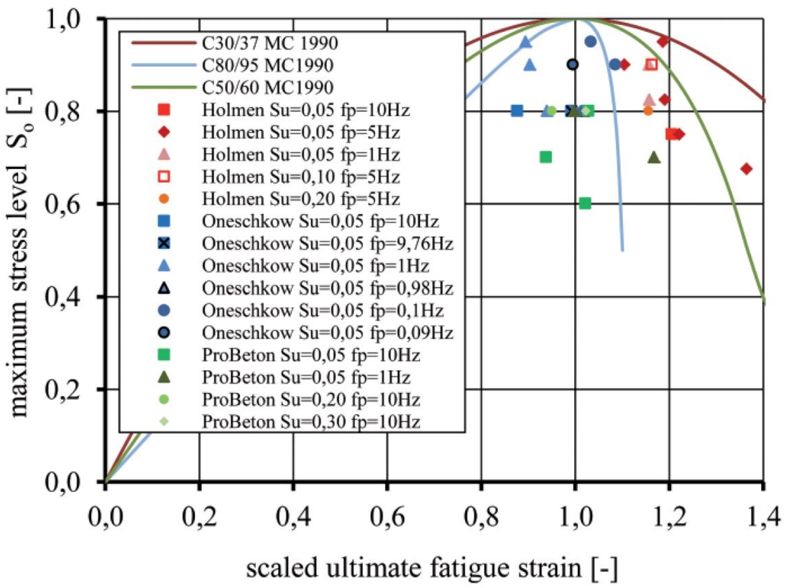


Figure 82: Fatigue failure strain compared to monotonic failure strain[53]

Most structures are designed to have a certain design life where it remains far from a state of fracture. Thus, the strain development in phase two of the strain propagation is of primary interest. Differentiation of strain contributions is important in order to efficiently approximate strains. The subject was briefly discussed in Section 3.12, with the effect of time on the strain evolution. A customary approach is to assign some of the plastic strain to creep effects and some to cyclic effects. The issue of elastic deformation should also be taken into consideration, especially as the elasticity modulus changes during cyclic loading.

Most proposed methods require significant fatigue testing in order to provide sufficient data. Hence, relating the monotonic stress strain curve to the cyclic stress strain curve has received a lot of attention. Notably, the concept of an envelope curve has been subjected to several hypotheses. The envelope curve traces the maximum stress and corresponding strain for all cycles. This yields different envelope curves depending on the loading arrangement. The use of the monotonic stress curve has been attempted to provide an upper limit to these curves. Von der Haar and Marx[115] summarize the three main hypotheses found in literature concerning envelope curves:

- The ultimate fatigue strain is smaller or insignificantly greater than the ultimate strain under monotonically increasing force-controlled compressive load.
- The ultimate fatigue strain is located on the decreasing branch of the envelope curve.
- The ultimate fatigue strain is located above the decreasing branch of the envelope curve.

Tests have shown that there exist cases which disprove all the hypothesis. Von der Haar and Marx[115] also presented their own rhelogical model for strains caused by fatigue loading. The model contains components which represent different mechanisms that contribute to strain evolution during cyclic loading. The proposed strain model consists of four different strain contributions as shown in Figure 83.

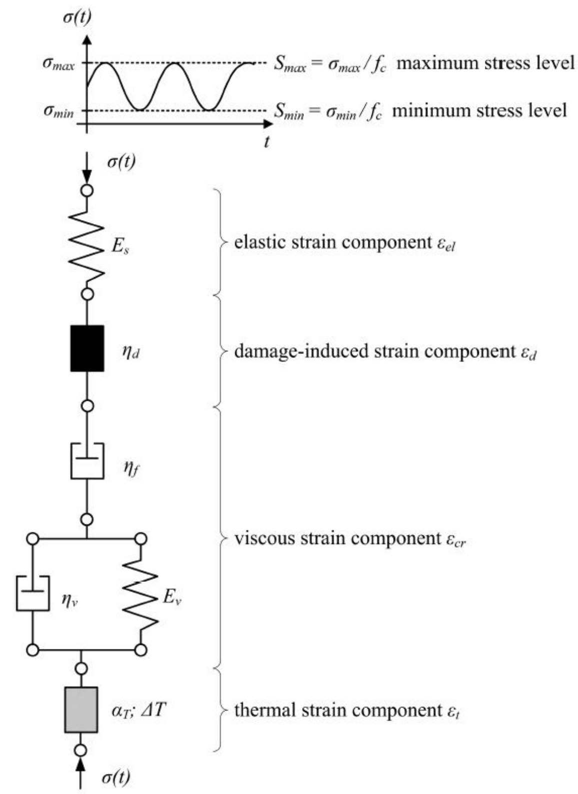
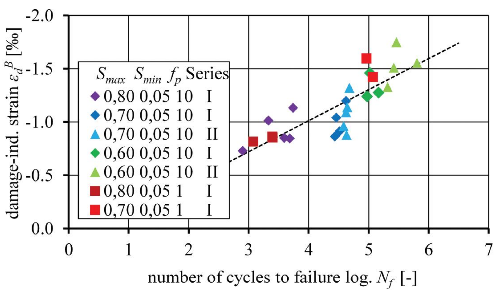


Figure 83: Additive strain model by von der Haar and Marx[115]

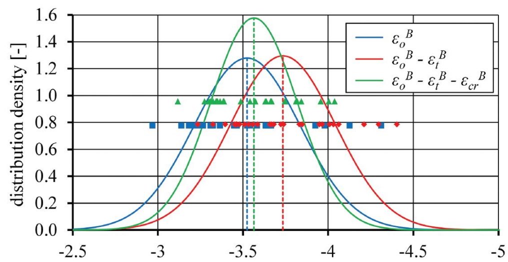
The components from Figure 83 account for the following:

- ε_{el} = The elastic deformation due to the overall change in elasticity
- ε_d = The plastic deformation due to cyclic damage
- ε_{cr} = The creep related strains (both elastic and plastic) due to a "creep-relevant" stress level.
- ε_t = Thermal strain due to changes in temperature from cyclic loading (mainly an issue in test facilities)

The separation of creep and plastic cyclic strains is important for the issue of fatigue strains. The most intuitive course of action is probably to use the mean stress level as the stress level of creep calculation. However, some have indicated the need for a higher level. Holmen[21] used the root mean square value as the "creep-relevant" stress level. This approach was partly adopted by von der Haar and Marx[115], who also indicated the creep-relevant stress level to be above the mean stress level. Their analytical model based the creep development on the method proposed in Model Code 2010. The creep in Model Code 2010 is defined as linear with the stress level when $S_{max} < 0.4$. When $S_{max} > 0.4$, the creep increases disproportional with the stress level. The model by von der Haar and Marx[115] therefore assumed that S_{max} influences the creep relevant stress level. For $S_{max} < 0.4$, the mean stress was assumed to correspond with creep-relevant stress level. For $S_{max} > 0.4$, the creep-relevant stress level would be higher than the mean stress level. For these values, the creep-relevant stress level was expressed as a function of the mean stress and the stress amplitude. This yields a creep-relevant stress level between mean stress and maximum stress level. A comparison of the analytic model and a test regime consisting of monotonically, permanent and cyclic loading tests revealed the strains believed to be due to cyclic loading. This is shown in Figure 84a. To gain applicability, more extensive verification is needed. However, the results from von der Haar and Marx[115] show the amount of the final yield strains which originates from the cyclic action itself for different values of S_{max}. The final strains are about 3.5‰, matching the ultimate strains normally seen in monotonic loading tests. About 1-1.5‰ can be attributed to the cyclic effect[115].



(a) The cyclic strain portion calculated from tests[115]



(b) The ultimate strain distribution density from experimental fatigue tests[115]

Figure 84: Results from the investigation of fatigue strain by von der Haar and Marx [115]

The model by von der Haar and Marx[115] has its shortcomings, including an inability to account for the stiffening effect on the loading stress-strain branch. However, it shows promise. The development of such a successful deformation model would not only improve the reliability of the SLS design, but also allow the stress redistributions to be accounted for in the ULS design.

It is evident that the rules of fatigue design are greatly simplified. These simplifications yield rules which are unable to account for both beneficial and potentially harmful effects. As a result, the need for safe designs forces engineers to apply an overly conservative approach.

5 Conclusion

Fatigue in concrete has received a lot of attention in the last few decades. However, the complexity of the subject emphasizes the need for further investigations. The large number of influencing factors are far from fully explored. Furthermore, the interaction of different factors and the comparison of the degree of influence from each factor have received minor attention. These relations can to some extent be deduced from experimental data. However, systematic comparison and analysis are not without its shortcomings and difficulties due to the variation in test parameters. The literature highlights 15 factors, with various degrees of influence, which should be considered to accurately predict fatigue capacity:

- Stress level
- Concrete composition
- Loading rate and frequency
- Loading waveform
- Moisture
- Rest periods
- Stress gradients
- Size effect
- Amplitude and stress reversal
- Multiple stage loading
- Temperature
- Time
- Multiaxial stress state
- Reinforcement
- Sea water

The development of a thorough understanding of these mechanisms is important as it may enable the transition from empirical formulas to analytical solutions. Furthermore, this development may also improve design rules and allow the inclusion of several influencing factors. Currently, design rules only explicitly account for stress level and amplitude. Consequently, there is a large potential for improvement. In addition, continuous development of new concrete types demands further testing. These tests are needed to verify if the new types exhibit similar behaviour as "normal concrete" and to discover any unknown effects. In conclusion, there is an extensive potential for further development and understanding of concrete fatigue.

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Appendices

A Summaries Sorted Chronological

Several factors influence fatigue life of concrete. Table 21 summaries all findings discussed in this thesis regarding the factors in a chronological order.

Table 21: Summary of findings in relation to concrete fatigue

Effect investigated	Author	Noticed effect	Notes	Year/ Source
Reinforcement	Muhlenbruch	Early investigation of bond fatigue, with proposed capacity curves for bond fatigue		1945[119]
Stress range	Murdock and Kesler	Larger amplitude reduces fatigue life	Compression	1958[75]
Loading Rate and Frequency	Assimacopoulos et al.	No consistent difference	$0.60 < S_{max} < 0.95$ & small number of specimens	1959[46]
Temperature	Assimacopoulos et al.	No change in fatigue capacity despite temperature increase & only higher frequencies yielded measurable temperature increases	Frequencies: 8.3 & 150Hz	1959[46]
Rest periods	Neville(Murdock)	Strength increase is proportional to rest periods up to 5 min		1960[20, 63]
Concrete Composition	Murdock	No significant variation in fatigue life of lightweight aggregate compared to NSC when stress level is expressed as a ratio of to static strength		1965[43]
Loading Rate and Frequency	Murdock	No effect	1.16-5 Hz tested	1965[43]
Multiple stage loading	Hilsdorf and Kesler	Stress range order and duration highly influence fatigue life	Flexural beams tested	1966[61]

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Effect investigated	Author	Noticed effect	Notes	Year/ Source
Rest periods	Hilsdorf and Kesler	Extended fatigue life with rests up to 5 min, longer periods yielding no further effect		1966[61]
Stress Gradient	Ople and Hulsbos	Stress gradient increased fatigue life	Compressive tests	1966[68]
Stess Level	Aas-Jacobsen	S_{max} has a linear relation to Log N	Formulated the famous Aas-Jacobsen formula	1970[37]
Reinforcement	Aas-Jacobsen	Cyclic loading may substantially increase the stress in the steel and relieve the concrete		1970[37]
Loading Rate and Frequency	Awad & Hilsdorf	Decreasing f_q leads to decreased fatigue life	$S_{max} = 0.9$	1971[47]
Loading Rate and Frequency	Sparks & Menzies	Decreasing f_q leads to decreased fatigue life	$S_{max} > 0.7$	1973[48]
Waveform	Tepfers et al.	Waveform influences both fatigue capacity and strains	Rectangular, triangular & sinusoidal	1973[54]
Temperature	Whaley and Neville	Lower frequency loading potentially yields large temperature increase. This depends on the stress range	Frequencies: 8.3Hz	1973[87]
Time	Whaley and Neville	The creep difference of cyclic and longtime static loading decreases in time		1973[87]
Stress Level	Jinawath	S_{max} has a linear relation to Log N		1974[6]
Multiple stage loading	Jinawath	Going from high to low stress level decreases fatigue life, indicating that the PM hypothesis is inaccurate	Two stage loading	1974[6]
Loading Rate and Frequency		Negligible effect	$S_{max} < 0.75$	1974[45]
Moisture	Raithby & Galloway	Moisture reduces fatigue life and moisture gradients increase damage	Bending of pure concrete beams	1974[45]

Table 21 – continued from previous page

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Table 21 – continued from previous page				
Effect investigated	**Author**	**Noticed effect**	**Notes**	**Year/ Source**
Active constant confining stress with uniaxial cyclic load	Takhar et al.	Confining pressure is beneficial if S_{max} <0.9		1974[109]
Multiple stage loading	Tepfers et al.	High stress followed by low stress tends to decrease fatigue life	Two stage loading	1977[82]
Stress range	Tepfers	Larger amplitude reduces fatigue life	Tension	1978[78]
Stress Level	Holmen	Nonlinear relation between S_{max} and Log N		1979[21]
Loading Rate and Frequency	Holmen	Decreasing f_q leads to decreased fatigue life	$S_{max} > 0.75$	1979[21]
Multiple stage loading	Holmen	Going from high to low stress level decreases fatigue life, indicating that the PM hypothesis is inaccurate	Two stage compressive loading	1979[21]
Multiple stage loading	Holmen	Random loading seems to have shorten fatigue capacity compared to the P-M rule	Multiple stage loading	1979[21]
Passive constant confining stress with uniaxial cyclic load	Desayi et al.	Similar benefit of confinement as for static application		1979[105]
Reinforcement	Rehm and Elighausen	Bar diameter and concrete strength do not influence bond fatigue if strength is taken as a ratio of static strength		1979[117]
Sea water	Paterson	Beneficial effects of sea water does not outweigh the degrading effects		1980[121]
Stress Level	Hsu	Established separate regression lines for low and high cycle fatigue	Considered several factor	1981[11]
Stress reversals	Tepfers	Some additional damage due to stress reversals	Some uncertainties in loading arrangement	1982[79]
Loading Rate and Frequency	P. D. Arthur et al.	No effect		1982[44]
Stress Level	Lenschow	Concrete fatigue is mainly affected by S_{max}		1982[30]

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Table 21 – continued from previous page

Effect investigated	Author	Noticed effect	Notes	Year/ Source
Loading Rate and Frequency	Sparks	No effect if the cyclic loading rate is compared to the static capacity at equivalent loading rate	Continuation of work by Sparks and Menzies[48]	1982[52]
Rest periods	Viswanathan	No effect	Specimens submerged or moist and resting periods of 9 and 99 sec	1982[67]
Biaxial cyclic loading	Traina and Jeragh	Biaxial loading is beneficial compared to uniaxially		1982[110]
Sea water	Arthur et al.	Sea water may increase fatigue capacity		1982[44]
Passive constant confining stress with uniaxial cyclic load	Shah et al.	Similar benefit of confinement as for static application		1983[106]
Concrete Composition	RILEM Comittee 36-RDL	Affects fatigue strength in similar manner as static strength and therefore not noticeable when fatigue strength is given as a ratio of static strength		1984[14]
Moisture	Cornelissen and Reinhardt	Increased water content reduces fatigue life	Centric tension	1984[55]
Stress Gradient	Cornelissen	Stress gradient increased fatigue life	Tension tests	1984[69]
Stress reversals	Cornelissen	More damage due to stress reversal beyond the expectation from a simple expansion of stress range		1984[69]
Passive constant confining stress with uniaxial cyclic load	Buyukozturk and Tseng	Similar benefit of confinement as for static application and significant difference in final strains compared to uniaxial stress state		1984[107]
Multiple stage loading	Hoff et al.	Going from high to low stress level decreases fatigue life, indicating that the PM hypothesis is inaccurate	Two stage compressive loading, lightweight aggregate	1984[84]
Concrete Composition	Håverstad and Jensen	Crack propagation through the aggregate itself	HSC with lightweight aggregate	1986[42]

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Effect investigated	Author	Noticed effect	Notes	Year/ Source
Table 21 – continued from previous page				
Multiple stage loading	Håverstad and Jensen	Four stage loading has mean miner sums far above 1, though significant scatter	Four stage compressive loading, lightweight aggregate	1986[42]
Moisture	Håverstad and Jensen	Specimens in water had 1/3 of the fatigue life compared to samples in air	Dry and wet samples, HSC with LWA	1986[42]
Biaxial cyclic loading	Nelson et al.	Biaxial cyclic loading is beneficial compared to uniaxially if $S_{max} > 0.75$		1988[111]
Concrete Composition	Petkovic	Fatigue life related to static strength shows little difference betwwen HSC and NSC, however the deformation behaviour changes noticeably	The observations is in agreement with Breitenbucher et al.[38] where a more uniform stiffness results in less stiffness degradation	1991[17]
Rest periods	Mallett	Possible explanation for effect of rest periods based on redistribution and strain reversal		1991[65]
Moisture	Petkovic	Increased water content reduces fatigue life, and even a natural water content may be damaging	Centric compression	1991[17]
Multiple stage loading	Oh	Decreasing subsequent loading decreases fatigue life	Four point bending, very large scatter in miner sums	1991[81]
Rest periods	Farhani	Damaging effect of rest periods	Specimens submerged and 500 sec resting period	1992[66]
Time	Bažant and Kim	The cyclic loading accelerates the creep compared to longtime loading		1992[104]
Reinforcement	Balázs	Bond fatigue strain exhibits similar behaviour as concrete		1992[116]
Multiple stage loading	Hordijk	High to low stress level increases fatigue life compared to the P-M rule	Tensile two stage loading	1992[80]
Loading Rate and Frequency	Zhang et al.	Decreasing f_q leads to decreased fatigue life	$S_{max} > 0.8$	1996[36]

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Effect investigated	Author	Noticed effect	Notes	Year/ Source
Stress reversals	Zhang et al.	Limited additional damage by exposure to stress reversals		1996[36]
Triaxial cyclic loading	Taliercio and Gobbi	Multiaxial cyclic loading in phase yields far larger benefit than those out of phase		1996[112]
Rest periods	Wu and Hachiya	Resting periods increase for fatigue life provided $S_m ax < 0.9$		2000[64]
Passive constant confining stress with uniaxial cyclic load	Hooi	onfinement is beneficial but the benefit decreases with increasing amount of cycles		2000[108]
Size effect	Zhang et al.	Similar strength reduction with larger specimens as seen in static application	Only considered for bending application	2001 [73]
Active constant confining stress with uniaxial cyclic load	Song et al.	Confining pressure is disadvantageous with tension-compression cyclic loading		2005[113]
Active constant confining stress along one axis with uniaxial cyclic load	Lü et al.	Biaxial compression is beneficial compared to uniaxial	Not discussed in text	2007[24]
Concrete Composition	Breitenbucher et al.	Coarse aggregate with similar stiffness as the cement paste yields less microcrack growth and thereby less degradation per cycle		2008[38]
Active constant confining stress with uniaxial tension cyclic load	Wang and Song	Confining pressure is disadvantageous with pure tension cyclic loading		2011[25]
Sea water	Neville	Summarizes general findings of sea water with respect to concrete		2011[20]
Loading Rate and Frequency	Oneschkow	Decreasing f_q leads to decreased fatigue life	$S_{max} > 0.80$ & HSC	2012[19]
Temperature	Elsmeier and Lohaus	Sufficient temperature accumulation gives a decrease in fatigue capacity	Frequencies: 1-10Hz	2014[88]

Table 21 – continued from previous page

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Table 21 – continued from previous page				
Effect investigated	**Author**	**Noticed effect**	**Notes**	**Year/ Source**
Loading Rate and Frequency	Hümme et al.	No clear influence of frequency	$S_{max} = 0.80$ & 0.6 & NSC	2016[53]
Temperature	Hümme et al.	Heating due to cyclic loading has a significant influence on fatigue capacity, and strain development	Frequencies: 1 & 10Hz	2016[53]
Time	Hümme et al.	Significant amount of strain due to time effects verified by tests		2016[53]
Multiple stage loading	Hümme et al.	Decreasing stress level increases fatigue life in compression for three stage loading	Conflicting result of multiple loading in compression compared to others	2016[53]
Waveform	Oneschkow	Waveform influences both fatigue capacity and strains	Triangular & sinusoidal loading	2016[18]
Size effect	Kirane and Bazant	Decreased fatigue life with increasing specimen size verified through test regime	Three point bending test	2016[77]
Reinforcement	Sun et al.	Factors influencing concrete fatigue have similar effect on bond fatigue		2017[118]
Multiple stage loading	Isojeh et al.	Proposed damage model with multiple amplitude compression tests based on ε_{II}	In agreement with general sequence effect in compression.	2017[29]
Frequency	Isojeh et al.	Decreasing f_q decreases fatigue capacity	1,5,10,20 Hz tested	2017[29]
Temperature	Otto et al.	The influence of temperature depends on the ability of specimen dehydration	Frequencies 1-10Hz	2018[23]
Concrete Composition	Scheiden and Oneschkow	Indications that change in aggregate type yields different damage mechanism		2019[39]
Moisture	Tomann and Oneschkow	Natural water content causes reduction in fatigue life to a larger extent than external water	Centric compression	2019[57]

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Effect investigated	Author	Noticed effect	Notes	Year/ Source
Reinforcement	Saito et al.	Windtower foundations failed prematurely due to bond fatigue		2020[120]
Multiple stage loading	Baktheer and Chudoba	Energy consideration seems to explain sequence effects in compression	Two stage loading	2021[41]

B Summaries Gathered From Text

This thesis has discussed the effect of several factors on fatigue life. The following tables summarise the findings on each factor in the same order as the thesis.

Table 22: Investigations of the effect of stress level with respect to fatigue

Author	**Noticed effect**	**Notes**	**Year/ Source**
Aas-Jacobsen	S_{max} has a linear relation to Log N	Formulated the famous Aas-Jacobsen formula	1970[37]
Jinawath	S_{max} has a linear relation to Log N		1974[6]
Holmen	Nonlinear relation between S_{max} and Log N		1979[21]
Hsu	Established separate regression lines for low and high cycle fatigue	Considered several factor	1981[11]
Lenschow	Concrete fatigue is mainly influenced by S_{max}		1982[30]

Table 23: Studies of the effect of concrete composition with respect to fatigue

Author	Studied composition	Noticed effect	Notes	Year/ Source
Murdock	Light weight aggregate	No significant variation in fatigue life of lightweight aggregate compared to NSC when stress level is expressed as a ratio of to static strength		1965[43]
RILEM Comittee 36-RDL	Composition as a whole	Influences fatigue strength in similar manner as static strength and therefore not noticeable when fatigue strength is given as a ratio of static strength		1984[14]
Håverstad and Jensen	HSC with lightweight aggregate	Crack propagation through the aggregate itself		1986[42]
Petkovic	HSC vs NSC	Fatigue life related to static strength shows little difference between HSC and NSC, however the deformation behaviour changes noticeably	The observations is in agreement with Breitenbucher et al.[38] where a more uniform stiffness results in less stiffness degradation	1991[17]
Breitenbücher et al.	Coarse aggregate	Coarse aggregate with similar stiffness as the cement paste yields less microcrack growth and thereby less degradation per cycle		2008[38]
Scheiden and Oneschkow	Coarse aggregate	Indications that change in aggregate type yields different damage mechanism		2019[39]

Table 24: Investigations of loading rate and frequency with respect to fatigue

Author	Frequencies studied [Hz]	Noticed effect	Notes	Year/ Source
Assimacopoulos et al.	8.33 & 150	No consistent difference	$0.60 < S_{max} < 0.95$ & small number of specimens	1959[46]
Murdock	1.16 - 5	No effect		1965[43]
Awad & Hilsdorf	Various	Decreasing f_q leads to decreased fatigue life	$S_{max} = 0.9$	1971[47]
Sparks & Menzies	Various	Decreasing f_q leads to decreased fatigue life	$S_{max} > 0.7$	1973[48]
Raithby & Galloway	4 - 20	Negligible effect	$S_{max} < 0.75$	1974[45]
Holmen	1, 5 & 10	Decreasing f_q leads to decreased fatigue life	$S_{max} > 0.75$	1979[21]
P. D. Arthur et al.	0.17 - 5	No effect		1982[44]
Sparks	Various	No effect if the cyclic loading rate is compared to the static capacity at equivalent loading rate	Continuation of work by Sparks and Menzies[48]	1982[52]
Zhang et al.	10^{-3} - 30	Decreasing f_q leads to decreased fatigue life	$S_{max} > 0.8$	1996[36]
Oneschkow	0.1, 1 & 10	Decreasing f_q leads to decreased fatigue life	$S_{max} > 0.80$ & HSC	2012[19]
Hümme et al.	1 & 10	No clear influence of frequency	$S_{max} = 0.80$ & 0.6 & NSC	2016[53]
Isojeh et al.	1,5,10,20	Decreasing f_q decreases fatigue capacity		2017[29]

Table 25: Investigations of waveforms with respect to fatigue

Author	Waveforms studied	Noticed effect	Notes	Year/ Source
Tepfers et al.	Rectangular, triangular & sinusoidal	Waveform influences both fatigue capacity and strains		1973[54]
Oneschkow	Triangular & sinusoidal	Waveform influences both fatigue capacity and strains		2016[18]

Table 26: Investigations of moisture content with respect to fatigue

Author	**Moisture conditions**	**Noticed effect**	**Notes**	**Year/ Source**
Galloway and Raithby	Dry, partly dry and wet	Moisture reduces fatigue life and moisture gradients increase damage	Bending of pure concrete beams	1974[45]
Cornelissen and Reinhardt	Dry and wet	Increased water content reduces fatigue life	Centric tension	1984[55]
Håverstad and Jensen	Dry and wet	Specimens in water had 1/3 of the fatigue life compared to samples in air	HSC with LWA	1986[42]
Petkovic	Dry, sealed and wet	Increased water content reduces fatigue life, and even a natural water content may be damaging	Centric compression	1990[17]
Tomann and Oneschkow	Dry, semi-dry, sealed, wet and submerged	Natural water content causes reduction in fatigue life to a larger extent than external water	Centric compression	2019[57]

Table 27: Investigations of rest periods with respect to fatigue

Author	**Rest length**	**Noticed effect**	**Notes**	**Year/ Source**
Neville(Murdock)	Various	Strength increase is proportional to rest periods up to 5 min		1960[20, 63]
Hilsdorf and Kesler	1,5,10,20 and 27 min	Extended fatigue life with rests up to 5 min, longer periods yield no further effect		1966[61]
Viswanathan	9 and 99 sec	No effect	Specimens submerged or moist	1982[67]
Mallett		Possible explanation for effect of rest periods based on redistribution and strain reversal		1991[65]
Farhani	500 sec	Damaging effect of rest periods	Specimens submerged	1992[66]
Wu and Hachiya	0-100 sec	Resting periods increase fatigue life provided $S_{max} < 0.9$		2000[64]

Table 28: Investigations of stress gradients with respect to fatigue

Author	**Stress gradient in**	**Noticed effect**	**Notes**	**Year/ Source**
Ople and Hulsbos	Compression	Stress gradient increased fatigue life		1966[68]
Cornelissen	Tension	Stress gradient increased fatigue life		1984[69]

Table 29: Investigations of size effect with respect to fatigue

Author	**Sizes considered**	**Noticed effect**	**Notes**	**Year/ Source**
Zhang et al.	50, 100, 150, 200, 300, 400, 500 and 800 mm	Similar strength reduction with larger specimens as seen in static application	Only considered for bending application	2001 [73]
Kirane and Bazant	40, 93 and 21 5mm height	Decreased fatigue life with increasing specimen size verified through tests	Three point bending test	2016[77]

Table 30: Investigations of stress range and stress reversals with respect to fatigue

Investigation	**Author**	**Noticed effects**	**Note**	**Year/ Source**
Stress range	Murdock and Kesler	Larger amplitude reduces fatigue life	Compression	1958[75]
Stress range	Tepfers	Larger amplitude reduces fatigue life	Tension	1978[78]
Stress reversals	Tepfers	Some additional damage due to stress reversals	Some uncertainties in loading arrangement	1982[79]
Stress reversals	Cornelissen	More damage due to stress reversal beyond the expectation from a simple expansion of stress range.		1984[69]
Stress reversals	Zhang et al.	Limited additional damage by exposure to stress reversals		1996[36]

Table 31: Investigations of multiple stage loading with respect to fatigue

Author	**Noticed effects**	**Note**	**Year/ Source**
Hilsdorf and Kesler	Stress range order and duration highly influence fatigue life	Flexural beams tested	1966[61]
Jinawath	Going from high to low stress level decreases fatigue life, indicating that the PM hypothesis is inaccurate	Two stage compressive loading	1974[6]
Tepfers et al.	High stress followed by low stress to tends decrease fatigue life	Two stage compressive loading	1977[82]
Holmen	Going from high to low stress level decreases fatigue life, indicating that the PM hypothesis is inaccurate	Two stage compressive loading	1979[21]
Holmen	Random loading seems to have shorten fatigue capacity compared to the P-M rule	Multiple stage loading	1979[21]
Hoff et al.	Going from high to low stress level decreases fatigue life, indicating that the PM hypothesis is inaccurate	Two stage compressive loading, lightweight aggregate	1984[84]
Håverstad and Jensen	Four stage loading has mean miner sums far above 1, though significant scatter	Four stage compressive loading, LWA	1986[42]
Oh	Decreasing subsequent loading decreases fatigue life	Four point bending, very large scatter in miner sums	1991[81]
Hordijk	High to low stress level increases fatigue life compared to the P-M rule	Tensile two stage loading	1992[80]
Hümme et al.	Decreasing stress level increased fatigue life in compression for three stage loading	Conflicting result of multiple loading in compression compared to others	2016[53]
Isojeh et al.	Proposed damage model with multiple amplitude compression tests based on ε_{II}	In agreement with general sequence effect in compression.	2017[29]
Baktheer and Chudoba	Energy consideration seems to explain sequence effects in compression	Two stage loading	2021[41]

Table 32: Investigations of temperature development with respect to fatigue

Author	**Noticed effects**	**Note**	**Year/ Source**
Assimacopoulos et al.	No change in fatigue capacity despite temperature increase & only higher frequencies yielded measurable temperature increases	Frequencies: 8.3 & 150Hz	1959[46]
Whaley and Neville	Lower frequency loading potentially yields large temperature increase. This depends on the stress range	Frequencies: 8.3Hz	1973[87]
Elsmeier and Lohaus	Sufficient temperature accumulation gives a decrease in fatigue capacity	Frequencies: 1-10Hz	2014[88]
Hümme et al.	Heating due to cyclic loading has a significant influence on fatigue capacity, and influences strain development	Frequencies: 1 & 10Hz	2016[53]
Otto et al.	The influence of temperature depends on the specimen dehydration	Frequencies: 1-10Hz	2018[23]

Table 33: Investigations of time with respect to cyclic loading

Author	**Noticed effects**	**Note**	**Year/ Source**
Whaley and Neville	The creep difference of cyclic and longtime static loading decreases in time		1973[87]
Bažant and Kim	The cyclic loading accelerates the creep compared to longtime loading		1992[104]
Hümme et al.	Significant amount of strain due to time effects verified by tests		2016[53]

Table 34: Investigations of multiaxial stress states with respect to fatigue

Investigation	**Author**	**Noticed effects**	**Note**	**Year/ Source**
Passive constant confining stress with uniaxial cyclic load	Desayi et al.	Similar benefit of confinement as for static application		1979[105]
Passive constant confining stress with uniaxial cyclic load	Shah et al.	Similar benefit of confinement as for static application		1983[106]
Passive constant confining stress with uniaxial cyclic load	Buyukozturk and Tseng	Similar benefit of confinement as for static application and significant difference in final strains compared to uniaxial stress state		1984[107]
Passive constant confining stress with uniaxial cyclic load	Hooi	Confinement is beneficial but the benefit decreases with increasing amount of cycles		2000[108]
Active constant confining stress with uniaxial cyclic load	Takhar et al.	Confining pressure is beneficial if S_{max} <0.9		1974[109]
Active constant confining stress along one axis with uniaxial cyclic load	Lü et al.	Biaxial compression is beneficial compared to uniaxial	Not discussed in text	2007[24]
Biaxial cyclic loading	Traina and Jeragh	Biaxial loading is beneficial compared to uniaxially		1982[110]
Biaxial cyclic loading	Nelson et al.	Biaxial cyclic loading is beneficial compared to uniaxially if $S_{max} > 0.75$		1988[111]
Triaxial cyclic loading	Taliercio and Gobbi	Multiaxial cyclic loading in phase yields far larger benefit than those out of phase		1996[112]
Active constant confining stress with uniaxial cyclic load	Song et al.	Confining pressure is disadvantageous with tension-compression cyclic loading		2005[113]
Active constant confining stress with uniaxial tension cyclic load	Wang and Song	Confining pressure is disadvantageous with pure tension cyclic loading		2011[25]

Table 35: Investigations of reinforcement with respect to fatigue

Author	**Noticed effects**	**Note**	**Year/ Source**
Muhlenbruch	Early investigation of bond fatigue, with proposed capacity curves for bond fatigue		1945[119]
Aas-Jacobsen	Cyclic loading may substantially increase the stress in the steel and relieve the concrete		1970[37]
Rehm and Elighausen	Bar diameter and concrete strength do not influence bond fatigue if strength is taken as a ratio of static strength		1979[117]
Balázs	Bond fatigue strain exhibits similar behaviour as concrete		1992[116]
Sun et al.	Factors influencing concrete fatigue have similar effect on bond fatigue		2017[118]
Saito et al.	Windtower foundations failed prematurely due to bond fatigue		2020[120]

Table 36: Investigations of effect of sea water with respect to fatigue

Author	**Noticed effects**	**Note**	**Year/ Source**
Paterson	Beneficial effects of sea water does not outweigh the degrading effects		1980[121]
Arthur et al.	Sea water may increase fatigue capacity		1982[44]
Neville	Summarizes general findings of sea water with respect to concrete		2011[20]

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Fatigue of Concrete

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