PROBABILISTIC-BASED SERVICE LIFE ANALYSIS OF REINFORCED CONCRETE COLUMNS SUBJECTED TO CORROSION DUE TO CARBONATION

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A RESEARCH DISSERTATION SUBMITTED TO THE SCHOOL OF POSTGRADUATE STUDIES, AHMADU BELLO UNIVERSITY, IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF DEGREE OF MASTER OF SCIENCE IN CIVIL ENGINEERING

DEPARTMENT OF CIVIL ENGINEERING,

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ZARIA, NIGERIA

AUGUST, 2021

DECLARATION

I hereby declare that this research work titled **Probabilistic-Based Service Life Analysis of Reinforced Concrete Columns Subjected to Corrosion due to Carbonation** is my research work and has been composed by me. It has not been presented in any previous work for the award of any degree. All sources of information used in this dissertation (published or unpublished) are duly acknowledged.

_____ _____

Amina Murtada KADI **Date**

CERTIFICATION

This dissertation titled **Probabilistic-Based Service Life Analysis of Reinforced Concrete Columns Subjected to Corrosion due to Carbonation** by Amina Kadi meets the regulations governing the award of Master of Science (MSc) Degree of the Post Graduate School of Ahmadu Bello University, Zaria and is approved for its contribution to knowledge and literary presentation.

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DEDICATION

This research is dedicated to Almighty ALLAH (SWT).

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All praises and thanks are to the Cherisher and Sustainer of the world for giving me the opportunity to complete this work successfully.

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ABSTRACT

Reinforced concrete (RC) structures are subjected to several sources of uncertainties that highly Affects their response. These uncertainties are related to the structure geometry, material properties and the loads applied. The lack of knowledge on the potential load, as well as the uncertainties related to the structural features shows that the design of RC structures could be made in a reliability framework. Most of the infrastructural development in Nigeria are in concrete and the environmentally unsustainable emission of carbon dioxide by industries and commercial outfits expose these concrete structures to carbonation.The parameter for load and resistance of reinforced concrete structures are random in nature and the current limit state design criteria in codes for such structures are largely deterministic. Field and Numerical experimentation were used for the Analysis. Monte Carlo Simulation (MCS) method of structural reliability was used for the Service Life Reliability analysis of the reinforced concrete column subjected to corrosion due to carbonation and the results were used to develop failure modes using Microsoft Excel Framework. The Service life reliability analysis of the reinforced concrete columns was based on the stochastic models of the basic design variables as well as the deterministic variables. The used corrosion rates are 0.02mm/year, 0.04mm/year, 0.06mm/year, 0.08mm/year, 0.1mm/year and 0.12mm/year. It was clearly established that at corrosion rates of 0.06mm/year, the service life reliability of the column dropped to 50% after 40 years corrosion exposure from 90% at the onset of the corrosion (10 years after construction).

Keywords; Corrosion, Reinforced Concrete, Monte Carlo Simulation, Reliability, Uncertainties, Carbonation, Service life

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CHAPTER ONE

INTRODUCTION

1.1 Background

The corrosion of reinforcing steel in concrete is now universally recognised as a major problem facing Civil Engineers today as they maintain an ever increasing ageing infrastructure (Broomfield, 2007). Corrosion consumes considerable portion of the budget of a country by way of either restoration measures or reconstruction. It is estimated that billions of dollars were spent annually on the maintenance and repairs of corroding reinforced concrete structures in North America alone (Darek, 2012).Nigeria loses 13.4 billion annually in the oil and gas industry segment. India loses more than $40 billion a year, (about 4 percent of the size of the total economy) due to corrosion in infrastructure and industry segments (Financial Express, 2012). The inspection, quality control, and maintenance strategies to detect such damages can be costly hence economic planning is mandatory. The economic losses and damage caused by the corrosion of steel in concrete makes it arguably the largest single infrastructure problem facing industrialized countries (Broomfield, 2007). The massive infrastructural development in Nigeria, is expected to be accompanied with massive service life issues especially for reinforced concrete structures that utilize steel as one of the major raw materials.

Corrosion is the disintegration of materials and its properties as a result of chemical or electrochemical reaction usually a metal and its environment facilitated by either carbonation or chloride ingress (Zaher and Samir, 2001; Torres-Acosta, and Sagues, 2004). Most metals corrode on contact with water (or moisture in the air) and oxygen. Depending upon the case, corrosion can be concentrated locally to form a pit, or it can extend across a wide area to produce general wastage (Bastidas-Arteaga and Bressolette, 2013).

The corrosion of steel bars embedded in concrete may lead to several undesirable consequences, such as potentially severe damage resulting in the loss of a cross-sectional area of steel that reduces both the capacity and ductility of the reinforcement (Fernandez,et.al., 2015), and accumulation of corrosion products, which occupy much larger volume than the original steel (Broomfield, 2007), thereby generating tensile stresses, which lead to cracking and spalling of concrete due to disproportionately large volume of the iron oxide Corrosion products accumulated around the reinforcement, commonly known as concrete cancer (Dehwah, et al. 2002). The volume expansion of rust not only causes splitting stresses but also affects steel-concrete bond properties (Al-Sulaimani, et al.1990 and Saether, 2010). Corrosion may affect the structural performance and integrity of reinforced concrete components to a considerable degree over the long run (CEB-fib, 2000) on exposure to moisture and air. Over time, this problem will then lead to the subsequent reduction of strength capacity thereby reducing the service life of the structure (Emilio, 2010). With increasing deterioration, the serviceability and functionality of the structure will be impaired and the load bearing capacity decreases thereby compromising its safety to carry applied loading.

Under normal environmental conditions, steel reinforcing bars embedded in reinforced concrete structures do not corrode. Usually, a thin film of iron oxide is present on the surface of the rebar when it is encased in the concrete. The high pH environment (approximately 13.5) associated with hydration of the Portland cement is usually sufficient to keep the protective film stable.

When the reinforcement starts to corrode, several damages occur. The four main consequences of corrosion are illustrated in Figure 1.1: (a) a loss of steel cross section due to the penetration of corrosion attack; (b) a loss in steel ductility due to the embrittlement caused by the corrosion inducing local acidification at the steel–concrete interface; (c) loss of steel–concrete bond due to

the reduction of bar cross section and the generation of iron oxides; and (d) cracking of concrete cover due to the pressure resulting from the production of oxides of higher volume than the parent steel (Andrade et al.1989; Rodriguez et al. 1994, Andrade, 2007).

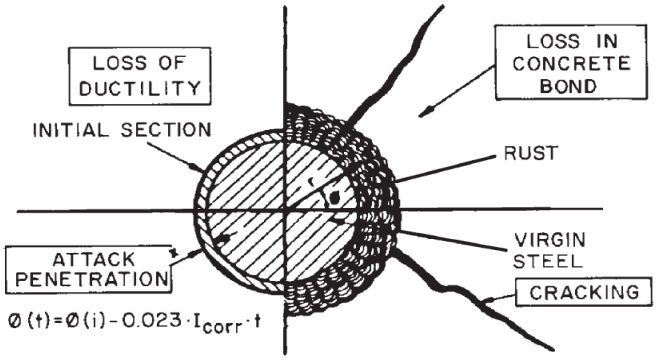


Figure 1.1: Consequences of reinforcement corrosion leading to loss of load-bearing capacity (Source: Andrade, 2007)

In a nutshell, the aforementioned process described reinforcing steel corrosion due to carbonation. Carbonation means the progressive neutralisation of the alkaline constituents of concrete by carbon dioxide in the air forming mainly calcium carbonate.

However, as a result of the uncertainties associated with the basic design variables such as the uncertainty in loading parameters, uncertainties in material properties as well as the uncertainties in geometrical parameters, service life prediction of reinforced concrete structures subject to carbonation or chloride ingress cannot be effective using deterministic approach. Hence the need for full probabilistic based analytical approach in order to efficiently accommodate these uncertainties in the structural strength and durability during the service life of the structure.

1.2 Problem Statement

It is well established in the literature such as in Andrade (2007) that, the environmentally unsustainable human activities such as cement manufacturing, lead to large presence of Carbon dioxide in the air in proportions ranging from 0.03% to 0.1% depending on the local contamination. This gas reacts with the alkalinity of cement phases to give $CaCO_3$ as the main reaction product. This process leads into a decrease of the pH value of the pore solution from pH>13 to pH<8. At this neutral pH value, the passive layer of steel disappears and a general and uniform corrosion starts. The CO_2, being a gas, penetrates through pore network of concrete. If the pores are filled with water, the gas dissolves in the liquid water and the penetration is then very slow. If the pores are not saturated with water, then the CO_2 can easily penetrate by diffusion and reach internal parts of the concrete cover. The carbonation reaction is then produced between the CO_2 gas and the alkaline ions present in the pore solution.

Most of the infrastructural development in Nigeria are in concrete and the environmentally unsustainable emission of carbon dioxide by industries and commercial outfits exposed these concrete structures to carbonation especially in the rainy season. Specific interest was developed in this research on reinforced concrete columns being then the major linkages between superstructures sand substructures in industrial, commercial and residential buildings. The specific interest is the prediction of safe service age of these structural members.

Likewise, today we have much interest in the use of blended cement with the view to reduce the amount of carbon dioxide emission by reducing the required amount of clinker. The low clinker binder produced by blending Portland cement with materials such as fly ash, rice husk ash lead

to much reduction of pH buffer capacity (Stepanoni et al., 2017) as a result of the reduction or even elimination of the calcium hydroxide reserve which is considered as one of the main reason for the corrosion inhibiting nature of Portland cement systems (Bertolini et al. 2013, Stepanoni et al.,2007).

In addition, it is now a well known fact that, the parameter for load and resistance of reinforced concretes structures are random in nature and the current limit state design criteria in codes for such structures are largely deterministic. Deterministic design is highly conservative and does not adequately accommodate random nature of design variables. Additional interest of this research is therefore to fully accommodate the uncertainties in loading and resistance parameters in the service life prediction of reinforced concrete columns subjection to corrosion due to carbonation.

1.3 Justification of the Research

Corrosion affects reinforced concrete structures negatively. Reinforced concrete structures that are exposed to corrosion due to carbonation suffer from loss of cross sectional area of steel reinforcement as well as concrete spalling due to expansion as a result of the formation of rust products, these are accompanied by reduced load carrying capacity. Reinforced concrete columns are the major links between concrete superstructures and substructures. Any progressive loss of load carrying capacity incurred by reinforced concrete columns subjected to corrosion may lead the their failure. Failure of reinforced concrete columns may result to the failure of part or whole of the superstructure they support. It is therefore important to access the status of the safety of the columns as corrosion proceeds and to identify the stage at which the safety of the structures is lower than acceptable limit. Likewise, analytical tools are readily available with the aid of computer hardware and software to facilitate full inclusion of the uncertainties in the

applied loading, material as well as geometrical parameters through full probabilistic approach. Hence the service life prediction of reinforced concrete columns subjected to corrosion due to carbonation was carried out in this research using probabilistic method.

1.4 Aim and objectives

1.4.1 Aim

The aim of this research is to carryout probabilistic based service life analysis of reinforced concrete columns subjected to corrosion due to carbonation.

1.4.2 Objectives

This aim would be achieved through the following objectives:

i. To determine the stochastic model for the basic design variables of the reinforced concrete columns considering column failure due to loss of reinforcing steel and failure due to crack propagation and concrete spalling.
ii. To Develop Microsoft Excel framework for Monte Carlo based structural reliability analysis of reinforced concrete columns subjected to corrosion.
iii. To determine the service life of the reinforced concrete columns subjected to corrosion using the developed framework.

1.5 Scope of the study

The study covers the probabilistic based service load prediction of Reinforced Concrete columns subjected to corrosion using Monte Carlo Simulation (MCS) Method. The stochastic models were generated from data obtained from the field during the research as well as data documented in the literature.

CHAPTER TWO

LITERATURE REVIEW

2.1 Preamble

In Engineering, when investigating the effects of corrosion, there are a few subjects that must be examined before looking at the area as a whole. First, the process of corrosion must be understood. This includes why corrosion occurs and what affects it. Then, any structural effects of corrosion must be examined to determine what influence these could have. Finally, but most importantly, previous work on this subject must be examined for comparison.

2.2 Reinforced Concrete

Concrete is best utilised in compression and steel is good in tension. When concrete and steel are combined, they form a composite member called reinforced concrete. In this combination, their individual weaknesses are overcomed and both strengths are utilised fully to increase the strength, stiffness, and durability of the structure (Najla et al., 2017). Reinforced concrete has been one of the most important structural materials widely used in construction application. It is very economical, cheap due to the availability of the raw materials, versatile allowing a wide range of forms and applications and it is usually durable and strong performing well throughout its service life if designed and executed in a proper way (Talakokula et al., 2014). However, in some cases, they do not perform adequately due to various reasons and one of the reason being corrosion of steel rebar.

2.3 Steel Materials

Steel is an alloy that consists mostly of iron and has a carbon content ranging from 0.2% to 2.1% by weight. The grade of steel determines its carbon content. Other materials used for alloying iron include; Manganese, Chromium, Vanadium and Tungsten. Varying the amount of alloying elements dictates the properties of the material such as; hardness, ductility and tensile strength. Steel with increased carbon content can be made harder and stronger than iron, but such steel is also less ductile than iron. Steel is selected for offshore construction because of its relatively low cost, ease of fabrication by welding, and moderately good mechanical properties (Smith and Hashemi, 2006).

2.4 Corrosion

Corrosion of the steel rebar in reinforced concrete occurs when the iron atoms combine with oxygen or chloride atoms to form a new compound. This is an electrochemical reaction that depends on the presence of water in the pores to act as an electrolyte. Initially, the rusting of steel in a normal environment, without the presence of concrete, is discussed. There are three distinct chemical reactions that occur:

$$Fe \rightarrow Fe^{2+} + 2e^{-} \quad (2.1)$$

$$O_2 + 4e^{-} + 2H_20 \rightarrow 40H^{-} \quad (2.2)$$

$$2Fe^{2+}\ 1/2O_2 + 4OH^{-} \rightarrow 2\ FeO\ .OH + H_20 \quad (2.3)$$

Each of these reactions occurs at a different location in the chemical system. The iron dissociates at the anode, and the oxygen and water react in the electrolyte (These then react at the cathode to form corrosion products at the cathode). This is a normal course for corrosion reactions of any

metal. Once concrete is involved, there are some differences. The concrete initially prevents corrosion by creating a basic environment. This passivates the steel by changing the form of corrosion products. Instead of producing the loose product FeO.OH and the FeO_2 reproduced. These substances adhere more closely to the surface of the bar. The progress of corrosion is thus limited by restricting oxygen access." The protection of the alkalinity can be overcome through either carbonation, or chloride ingress. The steel then begins to rust. The corrosion products are then similar to those found in the bare steel situation. With loss of protection due to chloride ingress, the corrosion reactions are then slightly different, as the pH has not been reduced. Instead it is $FeC1_2$ that is initially produced and this then forms $Fe(OH)_2$, or other more complex oxides and chloride compounds. So what effect does this have on the mechanical properties of the steel? The first effect is that there is smaller area of steel. Some steel has become this weak corrosion product.

Furthermore, the corrosion products have a larger volume than the original steel. This leads to stresses in the surrounding concrete and the potential for cracking. This obviously will have some effect on the performance of the reinforced concrete structure. It can also result in spalling of concrete cover. Various factors affect the rate of corrosion in concrete. These include the concrete quality, the thickness of cover, any cracking that may exist, the water and oxygen content of the pore system and either the chloride concentration or the depth of carbonation; depending upon what is causing corrosion. The concrete quality affects corrosion rate by limiting the access of any deleterious substances as well as oxygen. The quality can be improved by both reducing the water-cement ratio and the inclusion of supplementary cementing materials. Increasing the concrete cover thickness has a similar effect of reducing the amount of aggressive

substances that can enter. Cracks increase the amount of corrosion by providing pathways for deleterious chemicals and oxygen or water. The oxygen content and water content of the concrete are important as corrosion is an electrochemical process requiring the presence of both substances. If either of these substances is not present, then corrosion cannot occur.

2.4.1 Effects of corrosion on structural performance

Corrosion of the reinforcing steel will affect the structural performance of a reinforced Concrete section. In this section, discussion is made on effects other than loss of bond. Bond effects are discussed in the next section. The first effect is the influence of corrosion on the steel properties. This influence is in two ways. First, there is a loss of steel section. The corrosion reactions convert the iron atoms into some other molecule, as described previously. These molecules form a brittle, weak substance that does not participate in load sharing. Thus it can be assumed that the load of the steel reduces in proportion to the steel loss, as it has been done in many typical analyses (Yuan and Morosszeky, 1991). This would have an obvious influence on the capacity of the member and consequent effects on safety. The second effect corrosion has on structural performance is related to spalling. This is loss of the concrete around a bar due to its expansion. Spalling creates two difficulties. First, it can lead to a loss of bond. This will be discussed more extensively in the next section on bond. It also has the effect of loss of concrete section. This is more critical when the section that is spalling off is in the compression region. This can occur if the steel that is rusting is not the primary reinforcement but is included to control other effects, such as shrinkage and thermal movement. Unlike the concrete in the tension region, al1 the concrete in the compression region is used to resist load. Thus, if concrete is lost, this will have the effect of reducing the capacity of the member. This may not be critical at low levels of

concrete loss due to the design factors of safety. If allowed to continue, then a significant weakening can occur. The beams will then also be failing in compression, which is a brittle failure.

2.5 Mechanical properties of steel

The effects of corrosion on the mechanical properties of reinforcement have been studied by many researchers such as e.g. Apostolopoulos and papadakis (2008), Apostolopoulos and papadopoulous (2007); and Zhang et al. (2012). According to CEB-fib (2000), corrosion may be classified into two categories: general and local. General corrosion occurs when the corrosion is uniformly distributed along the reinforcement, so-called generalised corrosion, whereas localized corrosion forms local pits along the steel bar, named pitting corrosion. Generalized corrosion is commonly claimed to be caused by carbonation, whereas pitting corrosion is invariably associated with chloride contamination (CEB-fib 2000). Both pitting and generalised corrosion have important effects on the degradation of the mechanical properties of steel bars (Apostolopoulos and papadakis 2008). In the case of pitting, the ultimate strain is severely reduced by corrosion. It is sufficient with only 10 % of non-uniform corrosion to reduce the ductility of bars embedded in the concrete to below the minimum requirement specified in design codes for use in high ductility situations (Du et al. 2005a). Furthermore, Almusallam (2001) concluded that the stress-strain characteristics of corroded reinforcements indicate a decrease in the ductility with an increase in the corrosion level. Other steel parameters, such as yielding and ultimate stresses, are significantly reduced by corrosion (Apostolopoulos et al. 2006; Du et al. 2005a, 2005b; Fernandez et al. 2015). Different effects may occur due to the formation of the pits on a reinforcement bar subjected to tension; local bending on the pitted cross-section due to a displacement of the centre of gravity, as well as stress localization on the tip of the pit, may

explain the important drop in the main mechanical properties of the steel bar (Fernandez et al. 2015). The formation of large and localized strains due to such phenomena is also an important consequence; since the length of corrosion pit is short, the average strain in the entire bar becomes lower than the strain at a local pit (Stewart and Al-Harthy 2008), causing the corroded bars to fail at deformations much smaller than that of the original bar; thus, corrosion causes the reinforcement to behave in a brittle manner (Coronelli and Gambarova 2004).

2.6 Application of Reliability Analysis

Reliability of a structure is its ability to meet the construction requirements set out under specific conditions during the service life according to which it is designed. Reliability analysis includes complex procedures related to performing quantitative assessments of a structure at a specific stage. Reliability analysis also includes reliability calculations performed at the stages of preliminary design and detailed design, failure data analysis based on the results of special tests and operating testing. Reliability analysis is concerned with the rational treatment of uncertainties in structural engineering design and with methods for assessing the safety and serviceability of structures. Its application to design or single components is well established for both code writers and designers and it has also become an integral part of risk assessment and management procedures for a wide variety of structures.

Structural reliability analysis is concerned with the calculation and prediction of probability of limit state violation for engineers structures at any stage during their life; and in particular, structural safety is concerned with the violation of the ultimate or safety limit states for the structures (Melchers, 1987).

2.7 Structural Reliability Concept

During the last three decades the area of structural reliability theory has not only matured in a scientific and methodical sense but has also increasingly gained practical significance in a variety of different engineering application fields (Faber, 2008). These include offshore engineering, aeronautical engineering, naval architecture and civil engineering. As examples of the interdisciplinary success of structural reliability methods should be emphasized reliability based code calibration, reliability based structural assessment and risk based inspection and maintenance planning. These are all application areas where the methods of structural reliability have proven their value in supporting rational decision making, enhancing the efficiency of risk treatment and at the same time providing a transparent documentation of the basis for decision making.

2.8 Review of Related Works

Melchers (2021) presented new insights from the probabilistic modeling of corrosion in structural reliability analysis for fluid and gas containment facilities. The research established that, while extreme value theory is very useful for developing probability models for deteriorating processes for application in structural reliability analysis, it also can provide other insights relevant to material behavior and that might not otherwise have been revealed.

Zhang et al. (2021) investigated the random evolution process of corrosion in steel bars under a constant corrosion current density. They developed a probabilistic prediction model that combine the continuous-time Markov chain model with the Faraday law.

Zhang,B, Zhua,H, Chenb,J, and Yang ,O (2019). (2019) conducted Pull-out tests to investigate the influence of reinforcement corrosion and temperature exposure on bond performance between steel bar and concrete. The experimental results indicated that the deterioration of bond performance, including the bond strength, bond stiffness, bond energy dissipation, and residual bond stress, were influenced by the reinforcement corrosion and temperature exposure.

Wang et al., (2018) performed a comprehensive experimental study to quantify the effects of cyclic loading on the chloride ingress process and found that considering fatigue loading conditions have important effects in the lifetime assessment depending on the aggressiveness of the surrounding environment.

Bastidas-Arteaga E.,(2018) Carried out a stochastic model of reinforced concrete structures subjected to Corrosion-Fatique and climate change. The overall results indicated that the combined effect of corrosion and fatique leads to appreciable lifetime reductions ranging between 1.4 and 2.3% if fatique load is neglected while the lifetime reduction increases up to 7% under cyclic loading.

Dizaj et al., (2018) developed a new modelling technique using nonlinear fibre beam-column element to simulate nonlinear behaviour of rectangular RC columns, and verified it against experimental test results. This model accounts for the combined effect of corrosion on mechanical properties (strength and ductility), inelastic buckling, and low cycle fatigue of reinforcing bars as well as crack cover concrete and damaged core confined concrete (due to corrosion of confining reinforcement), which is able to predict multiple failure modes of flexural RC columns.

Kaura et al., (2014) Performed a probabilistic analysis using First Order Reliability Method (FORM) to assess reinforced concrete members subjected to chlorine ingress. From the results, it was observed that the increase in corrosion exposure time leads to a decrease in the capacity of the slab to resist applied loading and the extent to which the capacity is lost depends on the corrosion rate.

Bressolette et al., (2013) proposed a new model to assess lifetime of reinforced concrete structures subjected to corrosion-fatique deterioration processes. The model is applied to the reliability analysis of bridge girders located in different chloride-contaminated environments. Overall results show that coupled effect of corrosion-fatique on reinforced concrete (RC) structures affects strongly its performance leading to large reduction in the expected lifetime.
Chavez-Ulloa et al. (2013) in their research reported that inherent concrete porosity is a critical factor in steel reinforcement corrosion, but pore moisture content is the fundamental determining factor in development of corrosion process.

Bhargava et al., (2011) presented the estimation of the time-dependent failure probability using Monte Carlo simulation (MCS) that provides an insight about the dependence of failure probability of beam on the variability associated with the time-dependent strengths. Then, analytical formulations were presented for estimating time-dependent failure probability considering the variability in degradation functions. The results showed reasonably good agreement between the failure probabilities evaluated from analytical formulations and MCS.

In the work of Ying and Vrouwenvelder (2007), a procedure for service life prediction when spatial variability is considered was presented. The results was compared with the case where no spatial variability is considered.

Almusallam et al., (2001) found that adopting the minimum cross section to calculate strength did not decrease the strength of corroded rebars and Palsson et al., (2002) found the ratio of actual yield strength to ultimate tensile strength can rise with an increasing cross-sectional area loss. In addition, relevant studies have also shown that the yield strain and the ultimate strain of a corroded rebar drops with a growing average corrosion ratio.

Carlsson et al., (2000) presented a reliability analysis of corroded bridge columns, using Monte Carlo simulation and reliability analysis. The result indicated that despite apparently heavy damages, the reduction in safety was rather moderate after 32 years. Reliability based evaluation could be a very useful tool as a basis for decision about damaged structures and strategies for repair and inspection.

Al-Sulaimani et al., (1990) conducted an investigations on the bond deterioration induced by main bar corrosion. It was found that the corrosion at the early stage has positive influence on bond strength, but afterwards the bond strength decreased consistently with increased corrosion level. It is concluded that corrosion shows no negative influence before the appearance of visible corrosion induced cover cracking.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Preamble

This research involves both field and numerical experiments. The field work comprises data collection from the field. The data include strength and geometrical parameters of reinforced concrete structures. The reinforced concrete columns considered in the research are part of a two story reinforced concrete lecture hall located at the phase II of Ahmadu Bello University, main campus, Zaria, Nigeria. The numerical aspect involve structural reliability analysis using Monte Carlo simulation method.

3.2 Materials

The materials used in this research are In-situ concrete in existing reinforced concrete columns, reinforcing steel used for the same project. Non-destructive testing of concrete using schmdt rebound hammer was made. Also, data on columns geometry were obtained from the field. The field data were obtained on a two story reinforced concrete building located at ABU phase II (Plate 3.1). The datas are presented in Appendix 1. Also, data on the yield strengths of the

reinforcing steel used for the considered structure were obtained from the archive of the concrete laboratory of the Department of Civil Engineering, Ahmadu Bello university, Zaria.

The datas were subjected to statistical analysis using Easyfit. As mentioned in Chapter three, Easyfit is a data fitting software developed in Excel. From the analysis, the descriptive statistics and the appropriate probability distribution models for the design variables were determined.

3.3 Methods

As earlier mentioned, the research involved both field and numerical experimentation. These are presented in the subsequent sections.

3.3.1 Field Experiments

The field data collection involved measurement of the in-situ compressive strengths and geometrical parameters of the concrete. Data on the tensile strength of the steel reinforcement used for the same project was obtained from the concrete laboratory of the Department of Civil Engineering, Ahmadu Bello University, Zaria.

The in-situ compressive strengths were determined using schmdt rebound hammer non destructive testing method. The test is in accordance with BS 1881 Part 202 (1986) is illustrated in Figure 3.1. The operation of the rebound hammer is in such a way that, when the plunger is pressed against the surface of concrete, a spring controlled mass with a constant energy is made to hit concrete surface to rebound back. The extent of rebound, which is a measure of surface hardness, is measured on a graduated scale. This measured value is designated as Rebound

Number (a rebound index). Concrete with low strength and low stiffness will absorb more energy to yield in a lower rebound value.

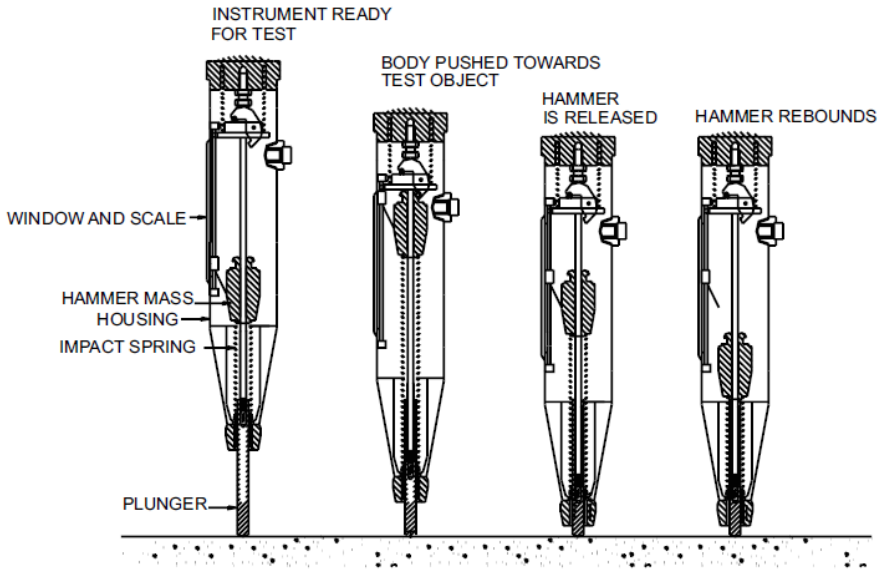


Figure 3.1: Schematic Diagrams of Operation of Rebound Hammer

Ten (10) rebound values were obtained at each of carefully selected and distributed points on selected reinforced concrete columns, ensuring that none of the values differ from the other by more than four (±4) to enable values for the actual concrete matrix to be obtained and not for stone or mortar. Plate 3, shows typical rebound hammer test during the field work. The results are presented in Appendix 1.

In addition to the compressive strength tests, data on the geometry of the columns were generated by measuring the depth and width of the columns at intervals of 500mm using steel tapes. The geometrical data are also presented in Appendix 1.

Data on the yield strength and geometrical distribution of the 25mm reinforcing steel used for the considered structures was obtained from the Concrete Laboratory of the Department of Civil Engineering. These data are also presented in Appendix 1. The considered structure is shown in Plate 3.1.



Plate 3.1. The structure under Investigation (Two story reinforced concrete building located at ABU phase)

3.3.2 Numerical Experiment

The numerical experimentation in this study is in two fold. First, involve the statistical analysis of the data obtained from the field. The second aspect involves statistical analysis of the field and laboratory data as well as structural reliability analysis.

3.2.2.1 Statistical Analysis

One of the core pre-requisites for structural reliability analysis is the determination of the stochastic models of the load, resistance and dimension for the failure modes of interest. In this research, the determination of the stochastic model were done using a statistical data fitting software written in Excel, called Easyfit. EasyFit is a data analysis and simulation software which enables us to fit and simulate statistical distributions with sample data, choose the best model, and use the obtained result of analysis to take better decisions. One of the advantages of using computer software to fit the data in probabilistic data analysis is that they have the ability to automatically fit data to a large number of distributions simultaneously. As the distributions are fitted, you can compare them to each other and choose the best given fit model.

The required output from the Easyfit are the descriptive statistics as well as probability distribution models fitted through tests of Goodness-of-Fit. These **tests**, as suggested by their very name, can be used to determine whether a certain distribution is fitted properly to the data or not. Calculating statistics of Goodness-of-Fit also helps to rank the fitted distributions according to quality of fit over the raw data. This particular characteristic feature of the software is very useful for comparing fitted models to each other. Most used Goodness-of-Fit tests include Kolmogorov-Smirnov, Anderson-Darling, and Chi squared tests.

3.2.2.2 Structural Reliability Analysis

The following steps were taken in this study for the reliability analysis:

i. Establishing limit states
ii. Identifying failure modes

iii. Formulating limit state functions

iv. Analyzing uncertainty

v. Evaluating reliability

vi. Assessing results

Limit states for excessive compression of the columns and that of column crack and spalling were considered in this study. Based on this limit states, the two failure modes considered are as follows:

vii. Failure due to loss of reinforcing steel

viii. Failure due to crack propagation and concrete spalling.

1. Failure Mode One: Lost of Steel Reinforcement

The compressive strength of corroded reinforced concrete columns depends mainly on the total available area of steel reinforcing bars. For uniform corrosion as shown in Figure 3.2, the total compressive reinforcement area as a function of time is

$$A_s = \frac{(N_{bar}\pi(\emptyset)^2}{4} \quad \text{for } t \leq T_i \qquad (3.1)$$

$$A_s = \frac{(N_{bar}\pi(\emptyset - 2v(t-T_i))^2}{4} \quad \text{for } t > T_i \qquad (3.2)$$

The performance function for the failure mode due to loss of reinforcing steel is given by Equation 3.3.

$$G(x) = \left(\frac{k_c B H f_c}{1+(k_{pi}p_{ieff})} + k_c A_s f_y\right) - \left(\gamma_g G + \gamma_q Q\right) \qquad (3.3)$$

Where A_s is given by Equation 3.1 or 3.2, k_c is a fitting parameter, B is the column width in mm, H is the column depth in mm, f_c is the concrete compressive strength in N/mm^2, f_y is the yield

strength of the steel reinforcement in N/mm^2, k_{pi} and p_{ieff} are Fitting parameters, A_s is the cross sectional area of the reinforcing steel in mm^2, γ_g is the modification factor for dead load, γ_q is the modification factor for live load, G is the dead load in N, Q is the live load in N, N_{bar} is the number of steel bars, ∅ is the diameter of the steel reinforcing bar in mm, v is the corrosion rate in mm/year, t is time in years, T_i is the corrosion initiation time in years.

2 Failure Mode Two: Crack Propagation and Concrete Spalling

The performance function for the failure of the reinforced column subjected to corrosion due to carbonation is given by Equation 3.4.

$$G(x) = w_{cr,i} - \left(0.05 + \left(\beta\left(vw_i\alpha t - \left(a_1 + \frac{a_2 c}{\emptyset + a_3 f_{tspl}}\right)\right)\right)\right) \quad (3.4)$$

$$G(x) = w_{cr,i} - w(t_p) \quad (3.5)$$

In Equations 3.4 and 3.5, $w_{cr,i}$ is the critical value of crack width in mm (i = 1: concrete crack, i = 2: concrete spalling), $w(t_p)$ is the actual crack width at t_p (time since initiation), β, a_1, a_2 and a_3 are fitting parameters, α is also a fitting factor, w_i is the factor of time that corrosion is active (wet period), v is the corrosion rate in mm/year, t is time in years, ∅is the diameter of bar in mm, f_{tspl} is the concrete splitting strength in N/mm^2.

3.3.2.3 Evaluation of Reliability Using Monte Carlo Simulation Method

The Monte Carlo Simulation (MCS) solves a problem by simulating directly the physical process, and it is not necessary to write down the differential equations that describe the behavior of the system.

The basic scheme of a simple or direct Monte Carlo simulation method consists of several steps (Pales et al., 2014).

i. Generation of individual random variables according to their respective probability distributions (for example: geometry of structure, material properties and load).

ii. Evaluation of the mathematical function of limit state which is formed by random variables.

iii. Determination of the failure probability of structure as a proportion of the number of simulations for which the limit state is less than zero to the total number of simulations.

The advantage of the method is its easy understandability, possibility to work with the function of limit state as a random variable.

The required mathematical relationship for Monte Carlo Simulation (MCS) method were given by Beck and Da Rosa (2006). In the case of a simple direct simulation adopted in this research, **X** (indicated in bold letters represents the vector of random variables) are generated according to

the distribution of probability density function $f_{\mathbf{x}}(\mathbf{x})$. The so called indicator function $I_{[g(x)]}$ is now introduced for each evaluation of limit state, which takes value 1 for failure and value 0 for reliability, thus:

$I_{[g(x)]} = 1$ for $g(x) < 0$ (3.6)

$I_{[g(x)]} = 0$ for $g(x) \geq 0$ (3.7)

Then, the probability of failure is calculated by multiple integration over the area of all random variables.

$$P_f = \int_{all\ x}^{i} I_{[g(x)]}.f_x(x)dx \quad (3.8)$$

Its mean value is computed using the summation of the indicator function:

$$E(P_f) = \frac{\sum_{i=1}^{n} I_{[g(x)]}}{n} \quad (3.9)$$

Where n is the number of the performed simulation.

Simulation result is loaded with statistical error, which can be expressed by the variance of estimated mean value of failure probability:

$$Var(P_f) = \frac{\sum_{i=1}^{n}\left(I_{[g(x)]} - E(P_f)\right)}{n-(n-1)} \quad (3.10)$$

3.3.2.4 Service Life Model of Reinforced Concrete

The service life of concrete is commonly modeled as a two stage process, defined respectively as the ‘initiation’ and the ‘propagation’ as shown in Figure 3.2.

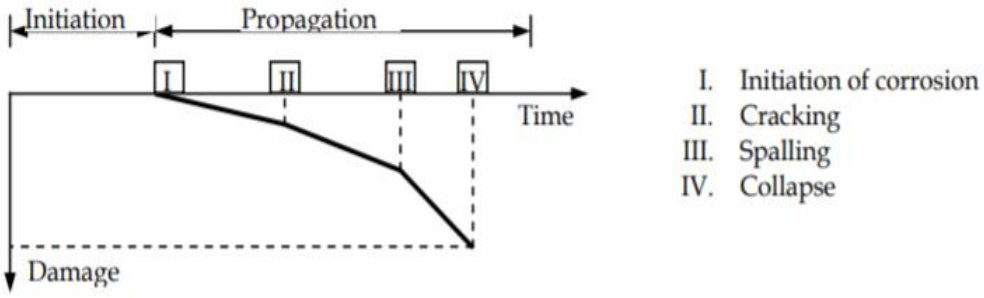


Figure 3.2: Main Events Related to Service Life of Concrete Structures

The initiation period is a period during which carbonation occur into the concrete cover, eventually depassivation takes place and rebar corrosion starts. Once corrosion of a rebar in concrete has been initiated, phenomena may occur such as reduced rebar cross-section, deterioration of concrete cover, cracking and spalling of concrete, loss of steel-to concrete bond etc. If corrosion proceed at a sufficiently high rate these phenomena may negatively affect performance and eventually structural capacity (Duracrete, 2000; Ying and Vrouwenvelder, 2007)

3.3.2.5 The Developed Service Life Prediction Framework

Based on Monte Carlo Simulation method, Microsoft Excel spreadsheet frameworks were developed for the evaluation of the structural reliability of the considered reinforced concrete columns subjected to corrosion due to carbonation considering the two limit state functions. The flow chart for the Monte Carlo Simulation Method for structural reliability is presented in Figure 3.3.

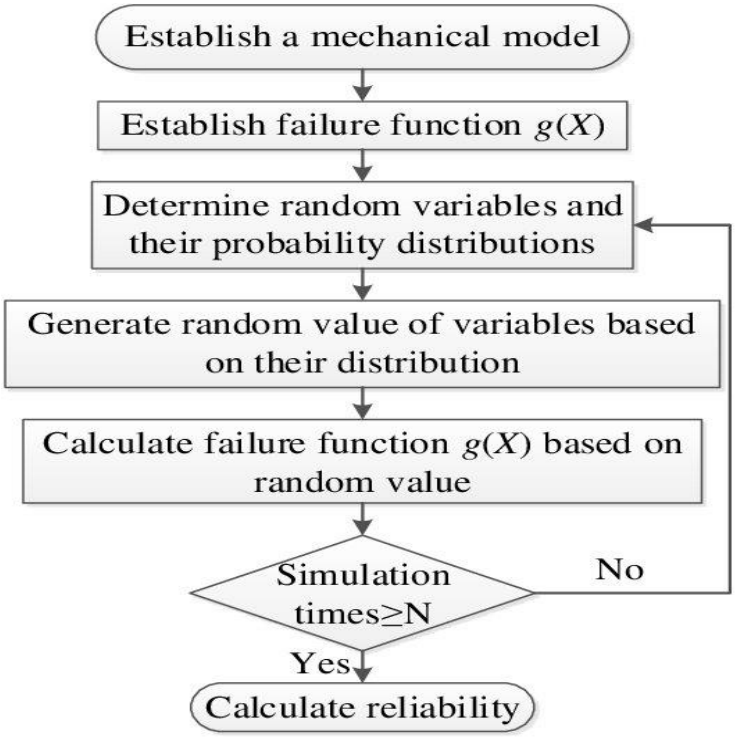


Figure 3.3: Flow Chart for Monte Carlo Simulation Method

3.2.2.6 Corrosion Rate

Corrosion rates are the measure of the depth of steel section lost in mm per year ((mm/year). Several data on corrosion rate due to carbonation are available in the literature such as Sergi et al. (1990), Saguez et al. (1997), Castro et al. (1990), Sergi et al. (2000), Varjonen (2004), Moreno et al. (2005), Mattila and Pentti (2008), Aligizaki (2014) and Kaura et al., (2014). The corrosion rates ranging from 0.02mm/year to 0.12 mm/year used in Kaura et al (2014) will be adopted in this research.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1. Preamble

In this chapter, the results obtained from both the field and numerical experiments is presented and discussed.

4.1.1 Analysis for the Compressive Strength of the Concrete

In this study, the data fitting was made using eleven probability distribution models namely:

i. Normal distribution

ii. 2 Parameter Lognormal distribution

iii. 3 Parameter Lognormal distribution

iv. Gumbel maximun distribution

v. Gumbel minimum distribution

vi. 2 ParameterWeibul distribution

vii. 3 Parameter Weibul distribution

viii. 2 Parameter Gamma distribution

ix. 3 Parameter Gamma distribution

x. 2 Parameter Frechet distribution

xi. 3 Parameter Frechet distribution

COMPRESSIVE STRENGTH OF CONCRETE

The descriptive statistics (distribution parameters) for the compressive strength of the concrete is given in Table 4.1.

Table 4.1: Distribution Parameters for the Compressive Strength of the Concrete

S/No.	**DISTRIBUTION**	**PARAMETERS**
1	Frechet	α=8.2 β=33.0
2	Frechet (3P)	α=5.5E+8 β=2.4E+9 γ=-2.4E+9
3	Gamma	α=54.0 β=0.66
4	Gamma (3P)	α=1.4E+2 β=0.41 γ=-23.0
5	Gumbel Max	σ=3.8 μ=34.0
6	Gumbel Min	σ=3.8 μ=38.0
7	Lognormal	σ=0.14 μ=3.6
8	Lognormal (3P)	σ=0.04 μ=4.9 γ=-96.0
9	Normal	σ=4.9 μ=36.0
10	Weibull	α=8.7 β=38.0
11	Weibull (3P)	α=4.0 β=19.0 γ=19.0

Also, the results of the test of goodness of fit are presented in Table 4.2, while the combined plots of the probability density functions are presented in Figure 4.1.

Table 4.2: Results of the Test of Goodness of Fit for Compressive Strength Data

S/No.	**DISTRIBUTION**	**KOLMOGOROV SMIRNOV**	
		Statistic	Rank
1	Frechet	0.15	11
2	Frechet (3P)	0.15	10
3	Gamma	0.09	7
4	Gamma (3P)	0.08	5

5	Gumbel Max	0.14	9
6	Gumbel Min	0.09	6
7	Lognormal	0.1	8
8	Lognormal (3P)	0.08	4
9	Normal	0.07	3
10	Weibull	0.05	1
11	Weibull (3P)	0.06	2

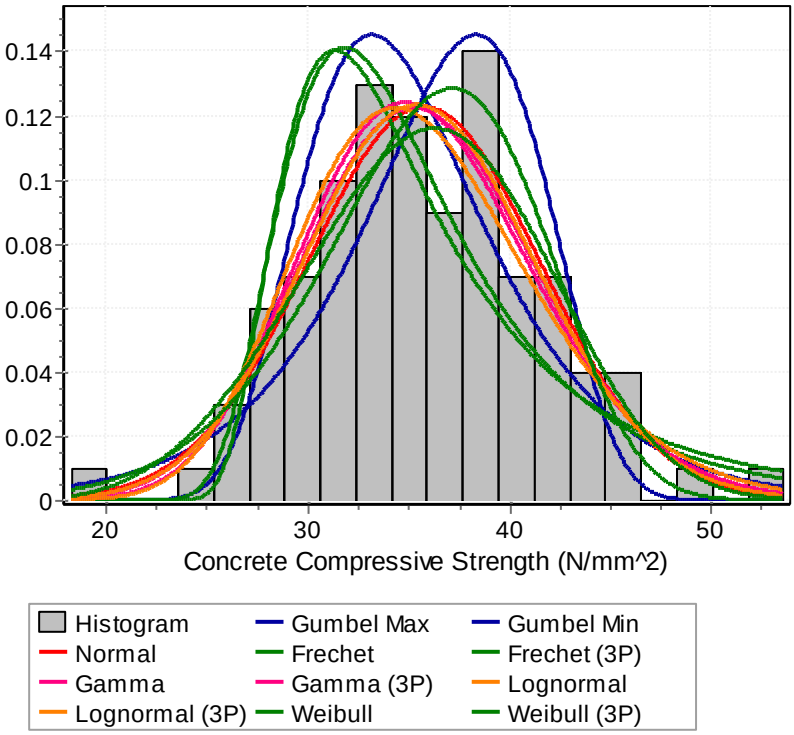


Figure 4.1: Pdf Plots of the Fitted Distributions of the Concrete Compressive Strength

In this study, Kolmogorov Smirnov test of goodness of fit was selected. From Table 4.2 and Figure 4.1, the critical value for K-S test at $\alpha = 0.05$, for the compressive strength is 0.2101. The critical values are embedded in the Easyfit Statistical Analysis Package. This value is greater than the K-S statistics of the Normal distribution, 2 Parameter Lognormal distribution, 3 Parameter Lognormal distribution, Gumbel maximum distribution, Gumbel minimum distribution, 2 ParameterWeibul distribution, 3 Parameter Weibul distribution, 2 Parameter Gamma distribution, 3 Parameter Gamma distribution, 2 Parameter Frechet distribution and the 3 Parameter Frechet distribution. The hypothesis that the compressive strength of the concrete values belong to each of the eleven tested distribution models is now accepted. This implies that, all the eleven distribution models can be used to model the compressive strength of concrete. However, considering the preferential ranking of the eleven fitted distribution model, it can be concluded that, the compressive strength of concrete can best be modeled using 2 parameter Weibul distribution, because it has the highest ranking of 1. Therefore, the most appropriate probability distribution model for the compressive strength is the 2 parameter Weibul distribution.

The probability density function of a Weibull random variable is given by:

$$f(x;\lambda,k) = \begin{cases} \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} \mathrm{e}^{-(x/\lambda)^k} & x \geq 0, \\ 0 & x < 0, \end{cases} \tag{4.1}$$

where $k > 0$ is the shape parameter and $\lambda > 0$ is the scale parameter of the distribution.

YIELD STRENTH OF THE STEEL

4.2.3 Analysis for the Yield Strength of the Reinforcing Steel

The distribution model parameters for the yield strength test data is presented in Table 4.3. Likewise the results of the test of goodness of fit as well as the pdf plots for the eleven considered distribution models are respectively presented in Table 4.3 and Figure 4.2.

Table 4.3: Distribution Model Parameters for Yield Strength Test Data

S/NO	**DISTRIBUTION**	**PARAMETERS**
1	Frechet	α=97.0 β=4.1E+2
2	Frechet (3P)	α=1.1E+8 β=5.1E+8 γ=-5.1E+8
3	Gamma	α=6.3E+3 β=0.06
4	Gamma (3P)	α=1.3E+2 β=0.45 γ=3.5E+2
5	Gumbel Max	σ=4.0 μ=4.1E+2
6	Gumbel Min	σ=4.0 μ=4.1E+2
7	Lognormal	σ=0.01 μ=6.0
8	Lognormal (3P)	σ=0.05 μ=4.6 γ=3.2E+2
9	Normal	σ=5.2 μ=4.1E+2
10	Weibull	α=97.0 β=4.1E+2
11	Weibull (3P)	α=2.9 β=15.0 γ=4.0E+2

Table 4.4: Results of Test of Goodness for Yield Strength of Reinforcing Steel

S/NO.	**DISTRIBUTION**	**KOLMOGOROV SMIRNOV**	
		STATISTIC	RANK
1	Frechet	0.12	11

2	Frechet (3P)	0.11	10
3	Gamma	0.05	2
4	Gamma (3P)	0.06	5
5	Gumbel Max	0.11	9
6	Gumbel Min	0.1	8
7	Lognormal	0.05	3
8	Lognormal (3P)	0.06	4
9	Normal	0.05	1
10	Weibull	0.09	7
11	Weibull (3P)	0.06	6

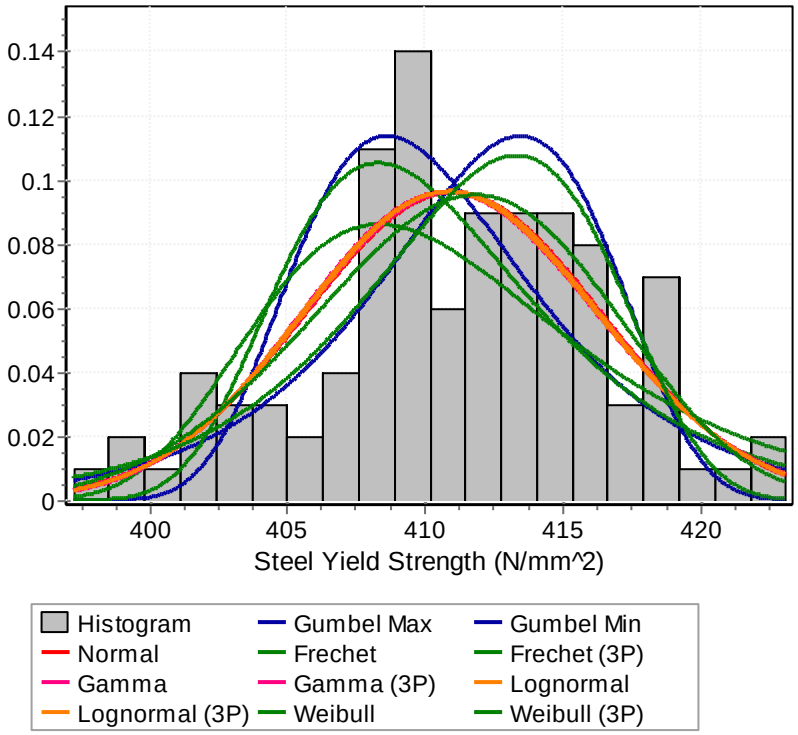


Figure 4.2: Pdf Plots of the Fitted Distributions of the Yield Strengths of Reinforcing Steel

From Table 4.4 and Figure 4.2, the critical value for K-S test at α = 0.05, for the compressive strength is 0.2101. This value is greater than the K-S statistics of the Normal distribution, 2 Parameter Lognormal distribution, 3 Parameter Lognormal distribution, Gumbel maximun distribution, Gumbel minimum distribution, 2 ParameterWeibul distribution, 3 Parameter Weibul distribution, 2 Parameter Gamma distribution, 3 Parameter Gamma distribution, 2 Parameter Frechet distribution and the 3 Parameter Frechet distribution. The hypothesis that the yield strength of the reinforcing steel values belong to each of the eleven tested distribution models is now accepted. This implied that, all the eleven distribution models can be used to model the yield strength of the reinforcing steel. However, considering the preferential ranking of the eleven fitted distribution model, it can be concluded that, the yield strength of reinforcing steel can best be modeled using Normal distribution, because it has the highest ranking of 1. Therefore, the most appropriate probability distribution model for the yield strength of reinforcing steel is Normal distribution.

The probability density function of a normal random variable is given by:

$$\mathrm{P}(x) = x = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)/(2\sigma^2)} \qquad (4.2)$$

4.2.4 Analysis for the Depth of the Reinforced Concrete Column

The distribution models parameters for the depth of the concrete column are presented in Table 4.5. Also the results of the tests of goodness of fit as well as the combined pdf plots for the eleven distribution models for the depth of the concrete columns are respectively presented in Table 4.6 and Figure 4.3.

Table 4.5: Distribution Model Parameters for the Depth of the Concrete Column

S/No.	DISTRIBUTION	PARAMETERS
1	Frechet	α=6.8E+2 β=3.0E+2
2	Frechet (3P)	α=64.0 β=35.0 γ=2.7E+2
3	Gamma	α=3.1E+5 β=9.8E-4
4	Gamma (3P)	α=2.8E+3 β=0.01 γ=2.7E+2
5	Gumbel Max	σ=0.42 μ=3.0E+2
6	Gumbel Min	σ=0.42 μ=3.0E+2
7	Lognormal	σ=0.0 μ=5.7
8	Lognormal (3P)	σ=0.02 μ=3.2 γ=2.7E+2
9	Normal	σ=0.54 μ=3.0E+2
10	Weibull	α=6.9E+2 β=3.0E+2
11	Weibull (3P)	α=76.0 β=24.0 γ=2.7E+2

Table 4.6: Results of the Test of Goodness of Fit for the Depth of the Concrete Column

S/No.	DISTRIBUTION	KOLMOGOROV SMIRNOV	
.		Statistics	Rank
1	Frechet	0.16	9
2	Frechet (3P)	N/A	
3	Gamma	0.09	2
4	Gamma (3P)	0.09	4
5	Gumbel Max	0.16	8
6	Gumbel Min	0.13	7
7	Lognormal	0.09	3

8	Lognormal (3P)	0.09	5
9	Normal	0.08	1
10	Weibull	0.11	6
11	Weibull (3P)	N/A	

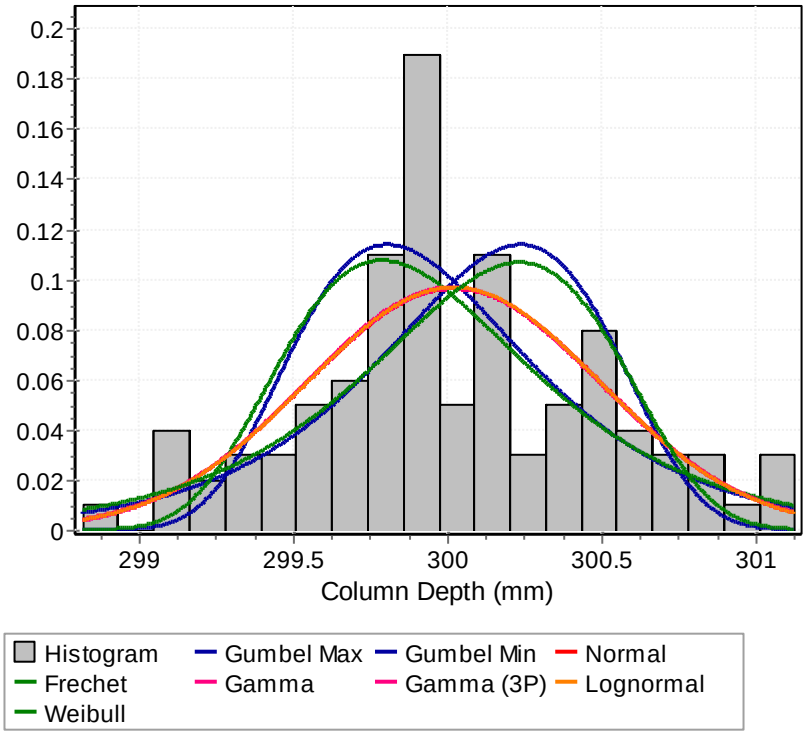


Figure 4.3: Pdf Plots of the Fitted Distributions of the Depth of the Concrete Columns

From Table 4.6 and Figure 4.3, the critical value for K-S test at $\alpha = 0.05$, for the depth of the column is 0.2101. This value is greater than the K-S statistics of the Normal distribution, 2 Parameter Lognormal distribution, 3 Parameter Lognormal distribution, Gumbel maximun distribution, Gumbel minimum distribution, 2 ParameterWeibul distribution, 3 Parameter Weibul distribution, 2 Parameter Gamma distribution, 3 Parameter Gamma distribution, 2 Parameter

Frechet distribution and the 3 Parameter Frechet distribution. The hypothesis that the depth of the column values belong to each of the eleven tested distribution models is now accepted. This implied that, all the eleven distribution models can be used to model the depth of the column. However, considering the preferential ranking of the eleven fitted distribution model, it can be concluded that, the depth of the column can best be modeled using Normal distribution, because it has the highest ranking of 1. Therefore, the most appropriate probability distribution model for the depth of the concrete column is Normal distribution.

4.2.5 Analysis for the Width of the Reinforced Concrete Column

The distribution model parameters for the width of the concrete column are presented in Table 4.7. Likewise, the results of the test of goodness of fit of the width of the concrete column as well as the combined pdf plots for the eleven considered distributions for the width of the concrete column are respectively presented in Table 4.8 and Figure 4.4.

Table 4.7: Distribution Model Parameters for the RC Column Width

S/No.	**Distribution**	**Parameters**
1	Frechet	α=75.0 β=5.9E+2
2	Frechet (3P)	α=2.1E+8 β=2.0E+9 γ=-2.0E+9
3	Gamma	α=3.6E+3 β=0.17
4	Gamma (3P)	α=35.0 β=1.7 γ=5.4E+2
5	Gumbel Max	σ=7.8 μ=5.9E+2
6	Gumbel Min	σ=7.8 μ=6.0E+2
7	Lognormal	σ=0.02 μ=6.4
8	Lognormal (3P)	σ=0.12 μ=4.4 γ=5.2E+2
9	Normal	σ=10.0 μ=6.0E+2
10	Weibull	α=73.0 β=6.0E+2
11	Weibull (3P)	α=3.0 β=32.0 γ=5.7E+2

Table 4.8: Results of the Test of Goodness of Fit for the RC Column Width

S/NO.	**DISTRIBUTION**	**KOLMOGOROV SMIRNOV**	
		Statistic	**Rank**
1	Frechet	0.07	8
2	Frechet (3P)	0.07	9
3	Gamma	0.06	5
4	Gamma (3P)	0.04	2
5	Gumbel Max	0.06	3
6	Gumbel Min	0.13	11
7	Lognormal	0.06	4
8	Lognormal (3P)	0.04	1
9	Normal	0.06	7
10	Weibull	0.12	10
11	Weibull (3P)	0.06	6

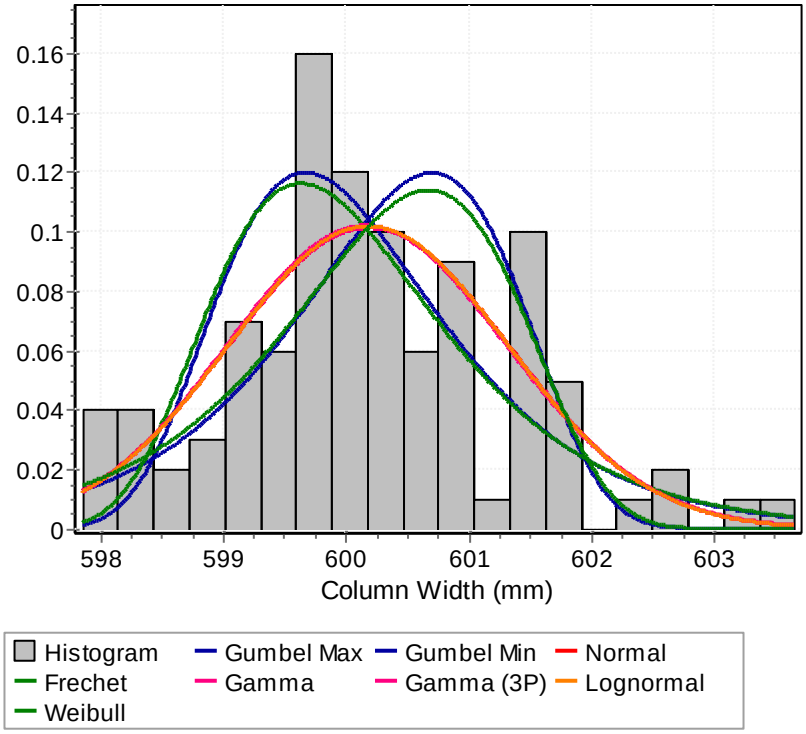


Figure 4.4: Pdf Plots of the Fitted Distributions of the Column Width

From Table 4.8 and Figure 4.4, the critical value for K-S test at $\alpha = 0.05$, for the depth of the column is 0.2101. This value is greater than the K-S statistics of the Normal distribution, 2 Parameter Lognormal distribution, 3 Parameter Lognormal distribution, Gumbel maximun distribution, Gumbel minimum distribution, 2 Parameter Weibul distribution, 3 Parameter Weibul distribution, 2 Parameter Gamma distribution, 3 Parameter Gamma distribution, 2 Parameter Frechet distribution and the 3 Parameter Frechet distribution. The hypothesis that the width of the column values belong to each of the eleven tested distribution models is now accepted. This implied that, all the eleven distribution models can be used to model the depth of the column. However, considering the preferential ranking of the eleven fitted distribution model, it can be concluded that, the width of the column can best be modeled using 3 Parameter Lognormal Distribution, because it has the highest ranking of 1.

The probability density function of a 3 parameter lognormal random variable is: giving by:

$$\frac{1}{x\sigma\sqrt{2\pi}}\ \exp\left(-\frac{(\ln x-\mu)^2}{2\sigma^2}\right) \tag{4.3}$$

4.3 Stochastic Models of the Basic Design Variables

As mentioned earlier, one of the major requirement of structural reliability analysis is the determination of the stochastic (statistical) models of the basic design variables of interest in order to fully model the uncertainties in the performance of the structure. The basic design variable appeared in the two performance functions of the RC column under corrosion are grouped in to three as follows:

1. The load action random variable
2. The resistance random variables
3. The random variable for the column components geometry.

The stochastic models considered in this research are presented in the following sections:

4.3.1 Stochastic Models for load action

Actual data on dead and live load uncertainties is not available for the Nigerian reality. In this research it is assumed that no significant difference exist in dead and live load uncertainties between Nigeria and what is reported in international references. Dead and imposed load statistics used in this research are based on data reported by Ellingwood et al., (1980) and McGregor (1976). The stochastic models of the load actions are presented in Table 4.9.

The mean dead and live load were established with reference to the load used in the structural design of the considered structure that are transferred to the critical column.

Table 4.9: Stochastic Models of the Load Action

Variable	Mean (kN)	Coefficient of Variation	Distribution Model
Dead load, G_k	774.12	0.10	Normal
Imposed load, Q_k	967.65	0.25	Gumbel

4.3.2 Stochastic Models of the Resistance Variables and Column Component Geometry

The stochastic models of the resistance variable were partly generated from the field/laboratory experimentation performed and presented in this study and partly from the data document in authoritative literature (Castro et al. 1990; Sergi et al. 1990; Sergi et al. 2000; Saguez et al. 1997; Duracrete, 1999; Rooij and Polder, 2002; Eurocode 1990, 2004; Varjonen, 2004; Moreno et al. 2005; Mattila and Pentti, 2008; Aligizaki, 2014 and Kaura et al., 2014). The stochastic models of the material properties are presented in Table 4.10.

Table 4.10: Stochastic Models of the Resistance Variables

Variable	Unit	Distribution	Mean	Standard Deviation	Reference
Column depth, H	mm	Normal	300	0.54	Experimental
Column width, B	mm	Normal	600	1.08	Experimental
Concrete Compressive Strength, f_c	N/mm^2	Weibul	35	5.7	Experimental
Yield Strength of the Reinforcing Steel, f_y	N/mm^2	Normal	410	4.7	Experimental
Diameter of the reinforcing Steel, Ø	mm	Normal	25	0.25	Kaura et al., 2014
Corrosion Rate due to Carbonation, v	mm/year	Deterministic	0.02 – 0.12	Nil	Kaura et al, 2014
Critical Crack Width (Concrete Crack), $w_{cr,1}$	mm	Normal	0.3	0.03	Duracrete, 1999
Concrete splitting strength ,	N/mm^2	Normal	4.4	0.2	Duracrete, 1999

$f_{t.spl}$					
Fitting parameter, β	-	Normal	9.5	2.85	Duracrete, 1999
Fitting parameter , α	-	Normal	9.28	4.04	Duracrete, 1999
Fitting parameter , a_1	mm	Normal	74.4	5.7	Duracrete, 1999
Fitting parameter , a_2	mm	Normal	7.3	0.06	Duracrete, 1999
Fitting parameter , a_3	mm/MPa	Normal	-17.4	3.2	Duracrete, 1999
Fraction of time that corrosion is active, w_i	-	Normal	0.9	0.06	Duracrete, 1999
Fitting parameter, k_c	-	Deterministic	1.0	Nil	Parameter
Fitting parameter , k_{pi}	-	Deterministic	1.0	Nil	Parameter
Fitting parameter , p_{ieff}	-	Deterministic	1.0	Nil	Parameter
Dead load safety factor, γ_g	-	Deterministic	1.35	Nil	Eurocode 1990 (2004)
Live load safety factor, γ_q	-	Deterministic	1.5	Nil	Eurocode 1990 (2004)
Time after corrosion initiation, t	years	Deterministic	1-35	Nil	
Corrosion initiation time, T_i	years	Deterministic	10	Nil	
Number of Reinforcing bars, N_{bar}	-	Deterministic	10	Nil	Structural Details of the Column
Pi, л	-	Deterministic	3.142	Nil	Parameter
Concrete cover to reinforcing steel, c	mm	Normal	41.1	1.4	Rooij &Polder, 2002

4.4 The Developed Framework for Reliability Analysis

An Excel based spreadsheet framework for the structural reliability of the considered RC columns subjected to corrosion due to carbonation was developed in this study with the aid of the program flow chart presented in Figure 3.3. The stochastic and deterministic models of Table 4.9 and 4.10 are the required input parameters. The output are the reliability and probability of failure obtained by evaluating the two performance functions (Equations 3.3 and 3.4) using Monte Carlo Simulation (MCS) method. The source codes developed framework are presented in Appendix 2.

4.5 Service Life Prediction of the RC Column

In this section, the results of the structural reliability analysis, considering the two performance (limit state) functions are presented.

4.5.1 Loss of Steel Reinforcement

4.5.1.1 Effects of Corrosion Exposure Time

As discussed earlier, one of the major effects of corrosion on the service life of reinforced concrete is the reduction or loss of the cross section of the reinforcing steel. The severity of this effect defends mainly on the corrosion rates and the corrosion exposure time. Six regimes of corrosion rates were considered in this research with reference to Kaura (2014). The six corrosion regimes are 0.02mm/year, 0.04mm/year, 0.06mm/year, 0.08mm/year, 0.1mm/year and 0.10mm/year. The corrosion was assumed to have started affecting the reinforcing steel after 10 years service life, and progress to 100 years. The Service life reliability was determined using Monte Carlo simulation method, with the stochastic models of the basic design variables as the random input. The deterministic input of the Monte Carlo Simulation include the corrosion rate of the steel reinforcement. The Service life reliability is the compliment of the probability of failure that has a maximum value of 1. The influence of corrosion exposure time on the service life reliability of the reinforced concrete column at various corrosion rates are presented in Figure 4.5. At the end of the corrosion initiation phase (10 years), the service life reliability for all corrosion rates in 0.9. That is, the available design service life of the concrete column is 90%. As the corrosion due to carbonation continued, the service life decreased proportionally. The severity of the loss of service life depend on the corrosion rates. For instance after 100 years of exposure, that is after 90 years of corrosion initiation, the service life reliability decreased from

90% to 76%, 64%, 52%, 42%, 37% and 32% respectively for corrosion rates of 0.02mm/year, 0.04mm/year, 0.06mm/year, 0.08mm/year, 0.1mm/year and 0.12mm/year.

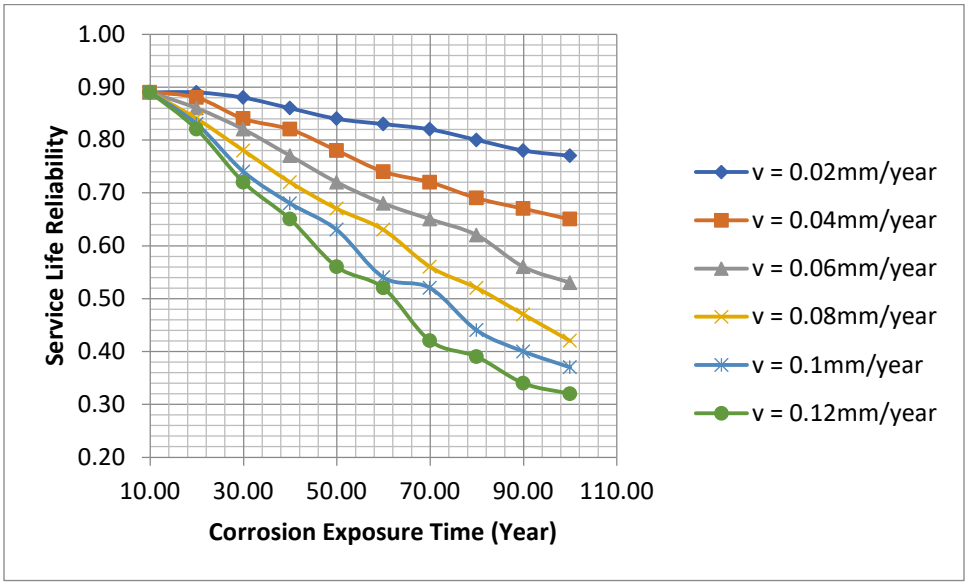


Figure 4.5: Effect of Corrosion Exposure Time on the Column Service Life Reliability for Various Corrosion Rates

The implication of these results on the safety of the column is that as the corrosion increases, its capacity to resist the design load with low failure probability is continuously reduced. For instance after 100 years of corrosion exposure, and with 0.06mm/year corrosion rate, the capacity of the column to resist the actions applied to it is slightly above 50%, signifying almost 50% failure probability. Therefore, the 0.06mm/year corrosion rate bench mark as well as 100years corrosion exposure time were used for sensitivity analysis to investigate the effect of dead to live load ratio, tensile strength of the reinforcing steel and compressive strength of the concrete material on the service life reliability of the reinforced concrete column.

4.5.1.2 Effects of Dead to Live Load Ratio

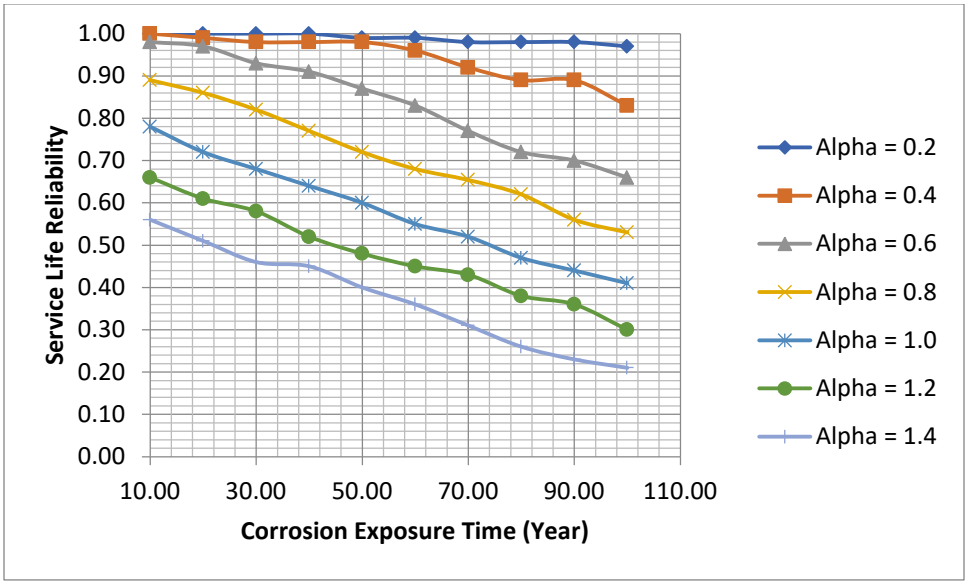


Figure 4.6: Effect of Corrosion Exposure Time with the Column Service Life Reliability for Various Dead to Live Load Ratio (v = 0.06mm/year)

The relationship between Corrosion exposure time and service life reliability of the considered reinforced concrete column subjected to various dead to live load ratio are presented in Figure 4.6. Seven dead to live load ratio regime were considered. The considered load ratio includes 0.2, 0.4, 0.6, 0.8, 1.0, 1.2 and 1.4. It is clear from the plot that, dead to live load ratio has significant influence on the service life reliability of reinforced concrete column. The results are based on carbonation corrosion rate of 0.06mm/year. For instance after 50 years of corrosion exposure, and at load ratios of 0.2, 0.4, 0.6, 0.8, 1.0, 1.2 and 1.4, the corresponding service life reliability are 100%, 99%, 85%, 70%, 58%, 46% and 40%. This implies that when the dead to live load ratio was changed from the design value of 0.8 to say 0.4 the service life reliability changed from 72% to 98%. (41% higher).

4.5.1.3 Effects of the Steel Yield Strength

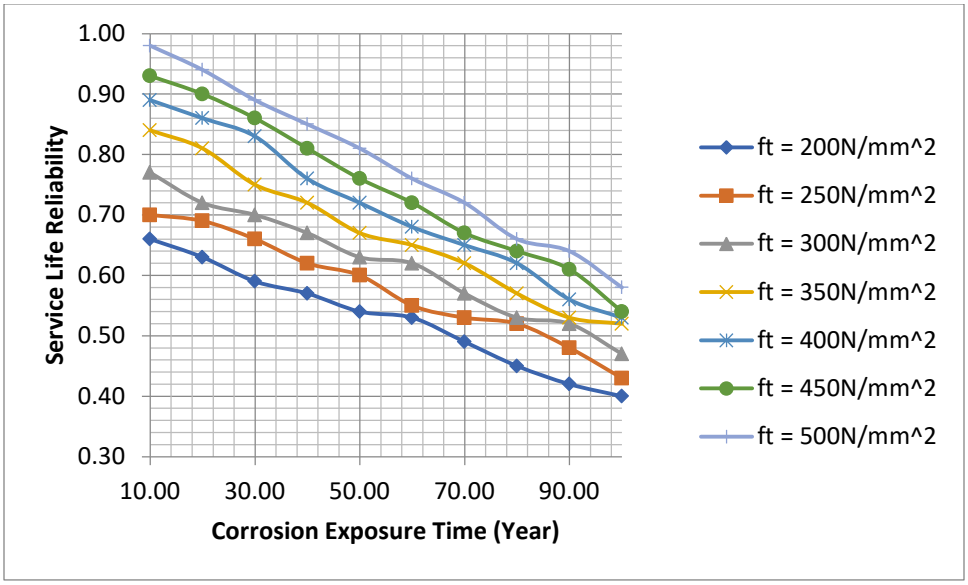


Figure 4.7: Effect of Yield Strength of Reinforcing Steel on the Service Life of the Column (v = 0.06mm/year)

Figure 4.7 shows the effect of corrosion exposure time on the service life reliability of the reinforced concrete column for different values of the steel yield strengths of 200N/mm^2, 250N/mm^2, 300N/mm^2, 350N/mm^2, 400N/mm^2, 450N/mm^2, 500N/mm^2.

It is clear from the plot that the service life reliability of reinforced concrete column exposed to corrosion due to carbonation is slightly affected by the yield strength of the steel reinforcement. For instance, for a steel yield strength of 200N/mm^2, the service life reliability of the column at the onset of the corrosion exposure is 0.66. After 50 years (40 year exposure to corrosion at corrosion rate of 0.06mm/year), the service life reliability dropped to 0.52. This signified a 14% load of service life reliability. However, at high steel yield strength of 500N/mm^2, considered as upper bound in this study, the service life reliability at the onset of corrosion is 98%. After 50

years (40 year corrosion exposure at corrosion rate of 0.06mm/year), the service life reliability dropped to 80% (this correspond to 18% loss of service life).

4.5.1.4 Effects of the Concrete Compressive Strength

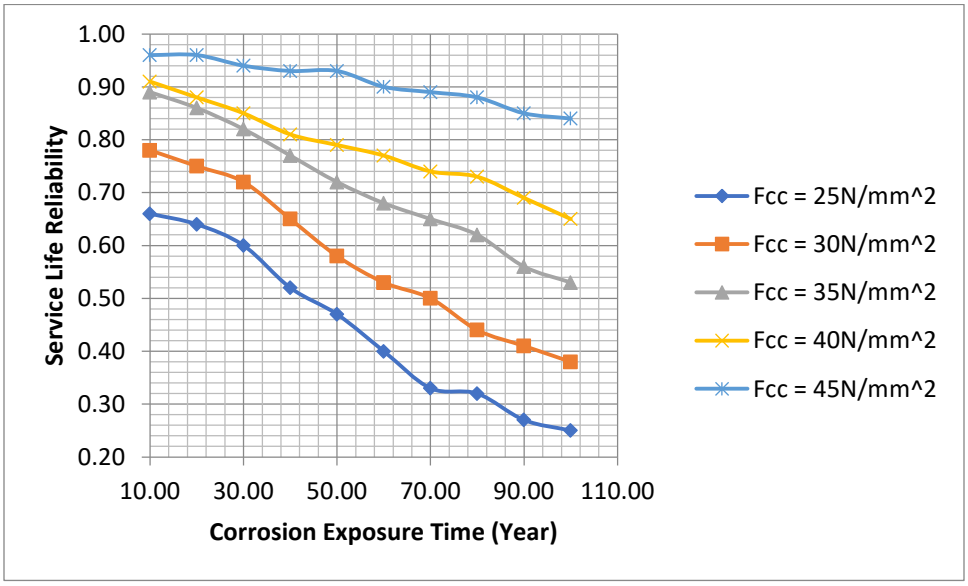


Figure 4.8: Effect of the Compressive Strength of the Concrete Material on the Service Life Reliability of the RC Column for Various Concrete Compressive Strength (v = 0.06mm/year)

Figure 4.8 presents the relationship between the compressive strength of the concrete and the service life reliability of the reinforced concrete column, considering various values concrete compressive strength. The considered values of the concrete compressive strength are 25N/mm^2, 30N/mm^2, 35N/mm^2, 40N/mm^2 and 45N/mm^2. Comparing this results with that presented in Figure 4.7, it is clear that the severity of the influence of concrete compressive strength is higher than that of the steel yield strength. For instance at the lower bound of the concrete compressive strength (25N/mm^2), the service life reliability of the column at the onset of the corrosion is 0.65. After 50 years (40 year corrosion exposure at corrosion rate of 0.06mm/year) the service life reliability of the column dropped to 47% (This implies 22% loss of service life reliability).

However, at the upper bound compressive strength (40N/mm^2), the service life reliability of the column at the onset of the corrosion is 0.95. After 50 years (40 year corrosion exposure at corrosion rate of 0.06mm/years), the service life reliability is 0.93 (signifying Just 3% loss of the column service life reliability). The implication of this result is that reinforced concrete corrosion due to carbonation can be arrested significantly with high strength concrete.

4.3.2 Crack Propagation

In this study, the service life reliability of the considered reinforced concrete column considering cracks propagattion in the concrete was also undertaken. In Figure 4.9, the relatioinship between the service life reliability and corrosion exposure time is presented. The investigation was made with carbonation corrosion rates of 0.02mm/year, 0.04mm/year, 0.06mm/year, 0.08mm/year, 0.10mm/year and 0.12mm/year.By carefully examing the plot, it is clearly observed that, up to 35 year from the construction of the column (25 years corrosion exposure time), the effect of the concrete crack on the service life reliability of the column is 100% at all instants. This implied that up to 35 years after construction of the column, its risk of failure due to corrosion is not significant. However, negative effect of crack progation on the performance of the column started manifesting after 25 years corrosion exposure (35 years after construction of the column).

The severity of the effect depend on the corrotion rate. For corrosion rates of 0.02mm/yeare, the service life reliability of the column remained intack throughout its design life (from 10 years to 90 years exposure to corrosion). When the corrosion rate is 0.04mm/year, no sign of the lost of service life reliability until after 70 years of column exposure to corrosion. The lost of services life reliability for 0.06mm/year, 0.08mm/year, 0.1mm/year and 0.12mm/year respectively began after 40 years, 30 years, 15 years and 10 years of exposure to corrosion. At 40 year corrosion

exposure, the respecive service life reliability of 0.02mm/year, 0.04mm/year, 0.06mm/year, 0.08mm/year, 0.10mm/year and 0.12mm/year are 1.0, 1.0, 1.0, 0.98, 0.92 and 0.76.

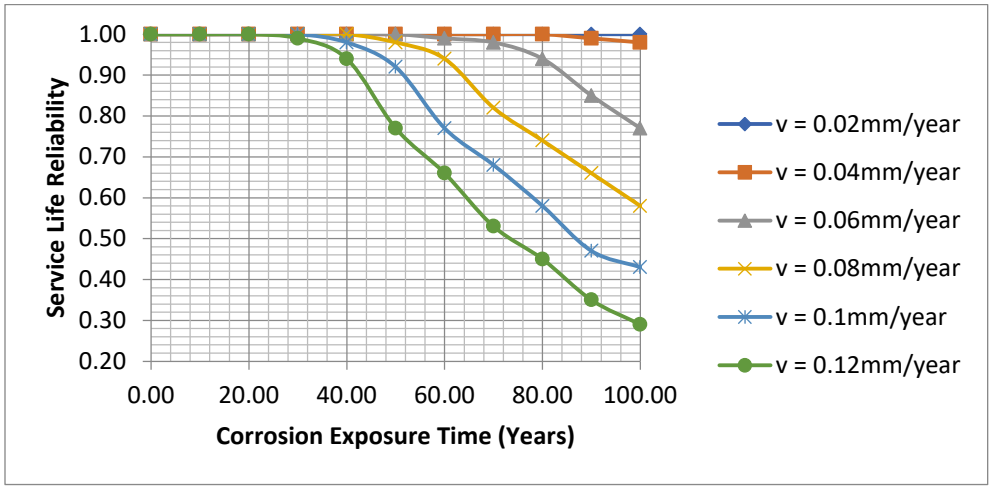


Figure 4.9: Effect of Corrosion Rate on the Service Life of the Column

4.3.3 General Comment

Comparing the two performance function; loss of steel reinforcement and crack propagation, their service life reliabilities clearly corresponded. The service life reliabilities for the loss of reinforcing steel and crack propagation modes of failure are both 0.3 for the maximum carbonation corrosion rate of 0.12mm/year at 90 years exposure to corrosion (100 years after the construction of the column.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this study, the service life structural reliability assessment of reinforced concrete column was undertaken. An existing reinforced concrete column located at Ahmadu Bello University phase II was considered for the reliability analysis. Based on the experimental and numerical experiment conducted, the following conclusions are made.

1. Data on the strength and geometrical parameter of the considered reinforced concrete column were obtained using field measurement and nondestructive test methods. The data on the used reinforcing steel were obtained from the Concrete laboratory of the Department of Civil Engineering. The field and the laboratory data, were analyzed on Easyfit statistical package. From the statistical analysis, the stochastic models of the strength and geometrical parameters were determined. The stochastic models include descriptive statistics (mean, standard deviation and coefficients of variation) and continuous probabilistic distribution models determined based on kolmogorov smirnov tests of goodness of fit implemented on the Easyfit. The stochastic models of the loading parameters were obtained from data reported in the international literature. Also the carbonation corrosion rates were obtained from previous work. The stochastic models were used to model the uncertainties in the basic design variables appeared in the two modes of failure of the reinforced concrete column subjected to corrosion due to carbonation. The failure modes are the failure due to loss of reinforcing steel and failure due crack propagation and spalling of the concrete section of the reinforced concrete column.

2. Monte Carlo Simulation (MCS) method of structural reliability was used for the Service Life Reliability analysis of the reinforced concrete column subjected to corrosion due to carbonation. Two Microsoft Excel Frameworks were developed for the implementation of the Monte carlo Simulation for each of the two modes of failures. The Excel Frameworks were linked with the Easyfit for the random data simulation required for the MCS method. The input to the two frameworks are the stochastic models of the basic design variables as well as the deterministic variables that appeared in the two performance functions of the two failure modes. The developed Excel MCS framework could be used for service life reliability analysis of axially reinforced concrete columns once the stochastic models are clearly defined.
3. The stochastic models of the basic design variables as well as the deterministic variables were used for the service life reliability analysis of the reinforced concrete column on the developed Excel Frameworks. Seven regimes of carbonation corrosion rates were used for the service life reliability analysis. The used corrosion rates are 0.02mm/year. 0.04mm/year, 0.08mm/year, 0.1mm/year and 0.12mm/year. For the failure mode 1, it was clearly established that at corrosion rates of 0.06mm/year, the service life reliability of the column dropped to 50% after 40 years corrosion exposure from 90% at the onset of the corrosion (10 years after construction). Comparing the two performance function; loss of steel reinforcement and crack propagation, their service life reliabilities clearly corresponded. The service life reliabilities for the loss of reinforcing steel and crack propagation modes of failure are both 0.3 for the maximum carbonation corrosion rate of 0.12mm/year at 90 years exposure to corrosion (100 years after the construction of the column

5.2 Recommendations

The developed Excel framework are recommended for use in the analysis of reinforced concrete columns that are likely to be exposed to corrosion due to carbonation. This will facilitate the prediction of the service life of the column, so that appropriate action can be adopted to reduce the effect if need be.

REFERENCES

Aligizaki K.K. (2014); Service Life Evaluation Of an Existing Reinforced Concrete Structure Based On Carbonation Induced Corrosion, CORROSION 2014 paper 4296.

Almusallam, A. A. (2001): "Effect of Degree of Corrosion on the Properties of Reinforcing Steel Bars." Construction and Building Materials, Vol. 15(8), pp. 361–368.

Al-Sulaimani, G. J., Kaleemullah, M., Basunbul, I. A., and Rasheeduzzafar. (1990): "Influence of Corrosion and Cracking on Bond Behavior and Strength of Reinforced Concrete Members." ACI Structural Journal, Vol. 87(2), pp. 220–231.

Andrade, C (2007) Corrosion of Steel Reinforcement in WIT Transactions on State of the Art in Science and Engineering, Vol. 28, WIT Press. www.witpress.com.

Andrade, C., Alonso, C. and Rodriguez, J. (1989). Remaining Service Life Of Corroding Structures. *IABSE Symposium on Durability*, Lisbon, September, pp. 359–363, 1989.

Apostolopoulos, C. A. (2007): "Mechanical Behavior of Corroded Reinforcing Steel Bars S500s Tempcore under Low Cycle Fatigue." Construction and Building Materials, Vol. 21(7), pp. 1447–1456.

Apostolopoulos, C. A., and Papadakis, V. G. (2008): "Consequences Of Steel Corrosion on the Ductility Properties of Reinforcement Bar." Construction and Building Materials, Vol. 22(12): pp. 2316–2324.

Apostolopoulos, C. A., and Papadopoulos, M. P. (2007): “Tensile and Low Cycle Fatigue Behavior of Corroded Reinforcing Steel Bars S400.” Construction and Building Materials, Vol. 21(4), pp. 855–864.

Apostolopoulos, C. A., Papadopoulos, M. P., and Pantelakis S. G. (2006): “Tensile Behavior of Corroded Reinforcing Steel Bars BSt 500s.” Construction and Building Materials, Vol. 20(9): 782–789.

Bastidas-Arteaga E.,(2018).Reliability of Reinforced Concrete Structures Subjected to Corrosion-Fatigue and Climate Change*International Journal of Concrete Structures and Materials DOI 10.1186/s40069-018-0235-x ISSN 1976-0485 / eISSN 2234-1315 (Received November 26, 2016, Accepted January 7, 2018.

Beck, A. T. and Da-Rosa, E. (2006). Structural Reliability Analysis using Deterministic Finite Element Programs. In Latin American Journal of Solids and Structures, vol. 3, pp. 197-222.

Bentolini L., Elsener, E., Redaelli, P. Pedeferri, P. and Polder, R. (2013). Corrosion of Steel in Concrete – prevention, diagnosis, repair. WILEY VCH second edition.

Bhargava et al. (2011): "Time-dependent reliability of corrosion affected RC beams-Part 2: Estimation of time-dependent failure probability," Nuclear Engineering and Design vol. 241, no.5,pp. 1385–1394, 2011.

Bressolette et al., (2013). probabilistic lifetime assessment of RC structures under coupled corrosion-fatique deterioration processes. Structural safety, Elsevier,2009, 31,pp.8496.

Broomfield, J. P (2007) Corrosion of Steel in Concrete: Understanding, Investigation and Repair. 2nd Edition London E & FN Spon Press.

BS 1881 Part 202 (1986). Testing concrete Part 202. Recommendations for surface hardness testing by rebound hammer. British Standards institution . 2 Park Street London WlA 2BS

Cady, P.D., and Weyers, R.E (1984). Deterioration rates of concrete bridge decks. J. Trans. Engr., ASCE, 110 (1), 34-44

Carlsson, F.; Jeppsson, J.; and Thelandersson, S. (2000) "Reliability analysis or corroded bridge columns," RILEM Publication, no. 12, pp. 271-276, 2000.

Castro P, Moreno E.I. Gensca J., (1990). Carbonation induced corroson of concrete coastal buildings in the north of Yucatan, Mexico. CORROSION'99 Paper 565.

CEB-fib. (2000): Bond of Reinforcement in Concrete. State-of-Art Report, Fédération internationale du béton, Bulletin 10, prepared by Task Group Bond Models, Lausanne, Swetzerland.

Chavez-Ulloa, E, Camacho-Chab, R. Sosa-Baz, M., Castro-Borges, P. and Perez-Lopez, T. (2013). Corrosion Process of Reinforced Concrete by Carbonation in a Natural Environment and an Accelerated Test Chamber. International Journal of Electrochem. Sci. Vol. 8. Pp. 9015-9029.

Coronelli, D, and Gambarova P. (2004): "Structural Assessment of Corroded Reinforced Concrete Beams: Modeling Guidelines." Journal of Structural Engineering, Vol. 130(8), pp. 1214–1224.

Darek, B (2012) A Frame Work for Stochastic Finite Element analysis of Reinforced Concrete Beams Affected by Reinforcement Corrosion. Thesis Submitted to the Faculty of Graduate and Postdoctoral Studies in Partial Fulfillment of the Requirements for the PhD degree in Civil Engineering, University of Ottawa, Canada.

Dario, C., Kamyab, Z. H., and Karin, L. (2013). Severely corroded RC with cover cracking. J. Struct. Eng., 139 (2), 221-232

Dehwah, H. A. F., Maslehuddin, M. and Austin, S. A. (2002), "Long-Term Effect of Sulphate Ions and Associated Cation Type on Chloride Induced Reinforcement Corrosion in Portland Cement Concretes", Cement and Concrete Composites, 24, 17-25.

Dizaj E, Madandoust R, Kashani MM.(2018): Exploring the impact of chloride-induced corrosion on seismic damage limit states and residual capacity of reinforced concrete structures. Struct Infrastruct Eng 2018;14(6):714–29.

Du, Y. G., Clark, L. A., and Chan, A. H. C. (2005a): "Effect of Corrosion on Ductility of Reinforcing Bars." Magazine of Concrete Research, Vol. 57(7), pp. 407–419.

Du, Y. G., Clark, L. A., and Chan, A. H. C. (2005b): "Residual Capacity of Corroded Reinforcing Bars." Magazine of Concrete Research, Vol. 57(3), pp. 135–147.

Duracrete (1999) Statistical quantification of the Variables in Limit State Functions. Document BE95-1347/R9, CUR, Gouda.

Duracrete (2000), Final Technical Report, Probabilistic performance based durability design of concrete structures, The European Union-Brite EuRam III, May 2000.

Ellingwood, B. Galambos, T. V. McGregor, I. G. and Cornell C. A. (1980). Development of Reliability-Based Load Criteria for American National Standard, A58.

Emilio B Bastidas-Arteaga (2010) A comprehensive probabilistic model of chloride ingress in unsaturated concrete.

Emilio, B (2018). Reliability of Reinforced Concrete SStructures Subjected to Corrosion-Fatigue and Climate Change University of Nantes.International Journal of Concrete Structures and Materials. DOI 10.1186/s40069-018-0235-x.

Eurocode 1990 (Eurocode 0, 2004). Eurocode-Basis of structural design. British standards. CEN Brussels

Faber, M. H. (2008). Interpretation of Uncertainties and Probabilities in Civil Engineering Decision Analysis. JCSS Joint Committee of Structural Safety. November, 2008.

Fernandez, I., Bairán J. M., and Marí A. R. (2015): "Corrosion Effects on the Mechanical Properties of Reinforcing Steel Bars. Fatigue and σ–ε Behavior." Construction and Building Materials, Vol. 101(2015), pp. 772–783.

Fernandez, I., Herrador, M. F., Marí A. R., and Bairán J. M. (2016): "Structural Effects of Steel Reinforcement Corrosion on Statically Indeterminate Reinforced Concrete Members." Materials and Structures, Published online.

Financial Express. (2012), http://www.financialexpress.com. Oct 10, 2012.

Humphrey, M. (2003) Development and structural Investigation of Monoque-Fibre composite Trusse, Phd Thesis, School of Civil Engineering, Queensland University of Technology. Australia.

Imbsen, R. A., Liu, W. D., Schamber, R. A., and Nutt, R. V. (1987) "Strength Evaluation of Existing Reinforced Concrete Bridges.". No. 292, Washington D.C., USA.

Kaura, J. M., Lawan A. Sadeeq J.A and Aliyu I. (2014) Probilistic Durability Analysis Of Reinforced Concrete Members With Corroded Reinforcing Steel. Jordan University Of Science and Technology. Vol. 8, No. 3. (July, 2014). pp 303-311.

Mackenzie, A. K., (1989*)* Effects *of* surface coatings *on* infrared measurements *of* thermoelastic responses. In Proceedings of International Conference on Stress and Vibration: Recent Developments in Industrial Measurement and Analysis (Ed. Stanley, P.), *SPIE1084*, *59 71*. London.

Mattila J. S. and Pentti M. J., (2008). Residual service life of concrete façade structures with reinforcement in carbonated concrete in Nordic climat, in Taylor made Concrete Structures – Walraven & Stoelhorst (eds). Taylor and Francis Group London (2008) p. 75-79.

McGregor J. G. (1976). Safety and Limit State Design for Reinforced Concrete. Canadian Journal of Civil Engineering. 10: pp. 484 – 513.

Melchers R E. (2021). New Insights from Probabilistic Modelling of Corrosion in Structural Reliability. Structural Safety, Elsevier, Vol. 88. Pp. 1-9.

Melchers R.E (1987). Reliability assessment and prediction, Ellis Horwood series in civil Engineering . Cooper struct, West Sussex England.

Milovan Stanojev (2018). Dragoslav Stojic. Reliability Analysis Of Structures. FACTA UNIVERSITATIS.series Architecture and Civil Engineering. Vol. 12,N^{o} 3, 2014, pp. 265-272. DOI:10.2298/FUACE1403265S

Moreno E.I., Solis-Cacano R.G., Lopez-Salar L.R., Carbonation induced corrosion in urban concrete structures, CORROSION 2005 paper 05263.

Najla Yas V , Mohammed Lasin K , Priyanka Dilip P (2017),Analysis of Hybrid Steel Trussed Concrete Beam Using ANSYS International Journal of Innovative Research in Science, Engineering and Technology Vol. 6, Issue 4, April 2017 ISSN(Online) : 2319-8753.

Pales D., Balcova, M. and Karandusovska, I. (2014). Calculation of Failure Probability of Constantly Loaded Cantilever Beam by Monte Carlo Method. Acta Technologica Agriculturae, volumr 3, 2014 pp 80-82.

Palsson R, Mirza MS. Mechanical response of corroded steel reinforcement of abandoned concrete bridge. ACI Struct J 2002; 99:157–62. http://dx.doi.org/10. 14359/11538.

Phillips. J. (1993)The Effect of Corrosion on the Structural Performance of New and Repaired One- Way Slabs, Ph.D. Thesis, University of Toronto, 1993, pg. 143.

Rodriguez, J., Ortega, L.M. and García, A.M. (1994). Assessment of structural elements with corroded reinforcements. Int. Conference on Corrosion and Corrosion Protection of Steel in Concrete, Sheffield, UK, ed. R.N. Swamy, pp. 171–185, 1994.

Rooij and Polder (2002). Investigation of the Concrete Structure of the Eastern Scheldt Barrier after 20 Years of Exposure to Marine Environment, TNO-Report 2002-C1-R2118-3 Final Version, January, 2003; Appendices, Investigation of the Influence of different Exposure zones on Concrete Parts of the eastern Scheldt Storm Surge Barrier, TNO Report 2002-C1-R2118-1A, July, 2002.

Sæther, I. (2010): "Structural Behaviour of Deteriorated and Retrofitted Concrete Structures."Ph.D. Thesis, Norwegian University of Science and Technology, Trondheim, Norway.

Saguez, A. A. Moreno, E. I. Morris, W. and Andrade, C. (1997). Carbonation in Concrete and Effect on Steel Corrosion, Florida Department of Transportation, June 1997.

Sergi G., Maleki M.T., Page C.L (2000). Control of reinforcement corrosion by surface treatment of concrete, Proc. Inst Civ. Engrs Structs & Bldings, 140 (2000) 85 – 100

Sergi, G., Lattey, S. E. and Page, C. L. (1990). Influence of surface treatments on corrosion rates of steel in carbonated concrete, in "Corrosion of Reinforcement in Concrete" ed. C.L. Page, K.W.J Treadaway, P.B. Bamforth, Society of Chemical Industry (1990) p. 409 – 419.

Smith, W. F. and Hashemi, J., (2006). Foundations of Materials Science and Engineering, 4th Edition; Mcgraws-Hill Book. Pp. 28-36.

Stepanoni, M., Angst, U. and Elsener, B. (2017). Corrosion Rate of Carbon Concrete 0 a critical review. Cement and Concrete Research

Stewart, M. G., and Al-Harthy A. (2008): "Pitting Corrosion and Structural Reliability of Corroding RC Structures: Experimental Data and Probabilistic Analysis." Reliability Engineering & System Safety, Vo. 93(3), pp. 373–382.

Talakokula, V., Bhalla, S. and Gupta, A. (2014), “Corrosion Assessment of Reinforced ConcreteStructures Based on Equivalent Structural Parameters Using Electro-Mechanical Impedance Technique”, Journal of Intelligent Material Systems and Structures, Volume 25 (4), pp 484-500.

Torres-Acosta, A., and Sagues, A. A. (2004). "Concrete cracking by localized steel corrosion geometric effects". ACI Materials Journal, 101, 501.

Varjonen, S. (2004). Accelerated carbonated concrete as corrosion environment, Nordic Concrete Research 31 (2004) 1 – 15.

Wang, X. H., Bastidas-Arteaga, E., & Gao, Y. (2018). Probabilistic analysis of chloride penetration in reinforced concrete subjected to pre-exposure static and fatigue loading and wetting-drying cycles. Engineering Failure Analysis, 84, 205–219..

Ying L. and Vrouwenvelder, T. (2007) Service Life Prediction and Repair of Concrete Structures with Spatial Variability. HERON. Vo. 52, No. 4. Pp. 251 – 268.

Yuan Y. and M. Marosszeky, (1991) "Analysis of Corroded Reinforced Concrete Sections for Repair", Journal of Structural Engineering v. 1 17 n. 7, July 1 99 1 , pg. 20 1 8-3 4

Zaher, K. and Samir, S. (2001). "Permeability and chloride penetration of concrete subjected to Gaza seawater exposures". Journal of the Islamic University of Gaza, 9 (2), 67-84.

Zhang, W., Chen, J., Yu, Q. and Gu, X. (2021) Corrosion Evolution of Steel Bars in RC Structures Based on Markov Chain Modelling. Structural Safety, Vol. 88pp. 1-14.

Zhang, W., Song X., Gu X., and Li S. (2012): “Tensile and Fatigue Behavior of Corroded Rebars.” Construction and Building Materials Vol. 34(2012), pp. 409– 417.

Zhang,B, Zhua,H, Chenb,J, and Yang ,O (2019). Evaluation of bond performance of corroded steel bars in concrete after high temperature exposure Laboratory of Concrete and Prestressed Concrete Structures of the Ministry of Education, Southeast University, Nanjing 210096, College of Civil Engineering and Mechanics, Xiangtan University,Xiangtan 411105,and College of Civil Engineering, Hunan University, Changsha 410082, China.

APPENDIX 1: Field Data for Strength and Column Geometry

S/No.	Compressive Strength (N/mm^2)	Steel Yield Strength (N/mm^2)	Column Depth (mm)	Column Width (mm)
1	27.7	410.7	295.4	597.8
2	42.5	415.5	351.8	609.1
3	38.4	409.7	329.1	573.9
4	31.8	411.8	285.4	596.8
5	33.5	415.8	272.6	594.8
6	32.4	415.2	344.3	626.0
7	46.4	409.8	321.4	595.5
8	36.2	406.7	308.3	602.0
9	33.5	408.4	318.0	616.2
10	40.0	400.2	295.6	608.9
11	37.4	406.4	288.5	585.1
12	36.1	416.4	286.8	592.2
13	29.9	409.0	293.7	588.5
14	33.2	412.1	269.2	593.0
15	34.4	415.5	274.5	610.4
16	34.1	413.4	299.8	594.0
17	37.0	391.7	306.2	617.6
18	37.4	407.9	325.4	596.0

19	38.6	414.5	289.7	591.1
20	39.9	403.4	343.0	605.3
21	32.2	408.2	327.7	590.3
22	29.7	413.2	265.2	594.6
23	27.7	405.8	297.6	603.7
24	39.6	408.3	289.5	587.9
25	37.6	418.4	311.4	598.6
26	38.2	404.2	264.8	599.3
27	39.7	408.0	340.5	590.7
28	39.3	411.1	307.2	590.5
29	35.1	421.3	327.9	591.5
30	33.1	414.3	306.9	600.7
31	35.1	411.0	317.6	581.2
32	37.6	416.7	289.8	597.8
33	35.1	403.7	340.6	599.9
34	36.1	413.1	303.1	609.8
35	35.8	411.3	327.8	588.0
36	43.9	401.4	325.6	624.6
37	31.2	398.6	296.8	600.3
38	32.2	408.6	300.0	601.9
39	41.2	398.0	294.2	615.2
40	41.7	406.5	314.7	597.5
41	35.8	398.4	288.2	592.8
42	27.4	416.4	301.5	596.8
43	25.3	411.4	276.2	599.3
44	44.2	416.4	239.8	592.1

45	35.9	414.4	331.9	593.0
46	35.7	403.2	280.7	598.8
47	31.0	411.4	282.3	602.7
48	29.3	412.8	303.0	629.7
49	37.9	409.2	259.3	596.0
50	41.3	416.1	338.8	600.2
51	27.5	410.8	329.2	613.9
52	34.0	408.2	295.3	598.5
53	38.8	409.9	324.8	598.7
54	37.1	412.2	256.5	586.1
55	29.7	417.4	304.8	616.9
56	45.0	415.3	277.6	594.5
57	29.4	406.8	284.7	591.6
58	33.2	402.5	330.4	593.0
59	32.5	418.4	297.4	589.7
60	40.6	409.8	317.2	604.2
61	38.8	407.4	321.6	593.9
62	41.1	413.6	274.1	588.7
63	33.4	407.3	262.7	623.4
64	41.3	415.2	334.6	611.4
65	33.0	419.5	324.1	604.9
66	25.7	400.9	283.0	596.6
67	29.9	410.3	306.7	611.3
68	28.4	413.2	329.0	586.2
69	39.8	394.3	286.7	583.9
70	34.8	409.4	302.6	590.5

71	38.4	411.3	276.3	596.3
72	30.0	415.3	298.8	593.8
73	33.6	415.2	308.5	614.9
74	34.1	414.9	264.5	601.0
75	32.3	410.5	307.2	605.1
76	34.3	408.9	297.3	598.5
77	32.8	410.8	285.0	606.3
78	34.5	412.5	319.5	583.6
79	35.8	415.7	281.4	597.4
80	36.0	411.3	277.3	592.2
81	40.0	413.0	342.8	594.8
82	33.8	412.4	323.5	610.3
83	42.1	416.4	283.7	604.6
84	41.1	397.8	305.2	601.1
85	25.8	414.4	290.9	597.4
86	39.1	412.4	317.8	598.8
87	33.4	403.2	288.1	598.1
88	37.9	408.6	304.1	589.7
89	27.9	411.7	305.4	587.1
90	39.6	419.2	291.1	594.8
91	36.8	418.1	281.6	604.6
92	32.0	411.3	298.8	596.0
93	34.9	410.5	302.9	591.2
94	27.9	410.5	307.4	585.5
95	38.0	411.4	294.4	599.0
96	36.2	409.9	307.2	602.6

97	40.2	412.3	311.3	604.4
98	33.8	410.6	310.9	583.6
99	34.1	415.6	306.0	594.8
100	35.7	424.3	305.6	604.0
101	27.7	410.7	295.4	601.0
102	42.5	415.5	351.8	628.4
103	38.4	409.7	329.1	614.0
104	31.8	411.8	285.4	602.6
105	33.5	415.8	272.6	602.6
106	32.4	415.2	344.3	597.7
107	46.4	409.8	321.4	584.4
108	36.2	406.7	308.3	601.2
109	33.5	408.4	318.0	597.0
110	40.0	400.2	295.6	599.8
111	37.4	406.4	288.5	619.1
112	36.1	416.4	286.8	603.6
113	29.9	409.0	293.7	608.1
114	33.2	412.1	269.2	586.4
115	34.4	415.5	274.5	611.5
116	34.1	413.4	299.8	594.7
117	37.0	391.7	306.2	594.3
118	37.4	407.9	325.4	603.0
119	38.6	414.5	289.7	620.8
120	39.9	403.4	343.0	598.0
121	32.2	408.2	327.7	574.2
122	29.7	413.2	265.2	596.1

123	27.7	405.8	297.6	604.7
124	39.6	408.3	289.5	602.9
125	37.6	418.4	311.4	589.5
126	38.2	404.2	264.8	584.5
127	39.7	408.0	340.5	610.1
128	39.3	411.1	307.2	593.7
129	35.1	421.3	327.9	603.5
130	33.1	414.3	306.9	580.3
131	35.1	411.0	317.6	599.6
132	37.6	416.7	289.8	597.5
133	35.1	403.7	340.6	601.6
134	36.1	413.1	303.1	586.3
135	35.8	411.3	327.8	593.9
136	43.9	401.4	325.6	590.7
137	31.2	398.6	296.8	600.9
138	32.2	408.6	300.0	604.8
139	41.2	398.0	294.2	618.5
140	41.7	406.5	314.7	591.2
141	35.8	398.4	288.2	594.3
142	27.4	416.4	301.5	611.6
143	25.3	411.4	276.2	618.9
144	44.2	416.4	239.8	596.0
145	35.9	414.4	331.9	593.4
146	35.7	403.2	280.7	596.3
147	31.0	411.4	282.3	595.2
148	29.3	412.8	303.0	580.3

149	37.9	409.2	259.3	595.5
150	41.3	416.1	338.8	587.4
151	27.5	410.8	329.2	605.8
152	34.0	408.2	295.3	606.2
153	38.8	409.9	324.8	595.9
154	37.1	412.2	256.5	594.5
155	29.7	417.4	304.8	608.6
156	45.0	415.3	277.6	600.1
157	29.4	406.8	284.7	601.4
158	33.2	402.5	330.4	601.9
159	32.5	418.4	297.4	596.0
160	40.6	409.8	317.2	595.9
161	38.8	407.4	321.6	593.5
162	41.1	413.6	274.1	607.1
163	33.4	407.3	262.7	597.8
164	41.3	415.2	334.6	578.3
165	33.0	419.5	324.1	598.1
166	25.7	400.9	283.0	606.1
167	29.9	410.3	306.7	601.4
168	28.4	413.2	329.0	614.8
169	39.8	394.3	286.7	603.0
170	34.8	409.4	302.6	598.9
171	38.4	411.3	276.3	592.1
172	30.0	415.3	298.8	592.3
173	33.6	415.2	308.5	609.3
174	34.1	414.9	264.5	607.8

175	32.3	410.5	307.2	605.5
176	34.3	408.9	297.3	591.3
177	32.8	410.8	285.0	606.8
178	34.5	412.5	319.5	600.7
179	35.8	415.7	281.4	610.3
180	36.0	411.3	277.3	595.2

Appendix 2: The Developed Excel Based Service Life Prediction Framework

Appendix 2a: Failure due Loss of are of Reinforcing Steel

Appendix 2a, Page 1:

KC	B	H	FCC	KPI	PIEFF	NBARS	PI
1.00	300.36	598.55	40.98	1.00	1.00	10.00	3.14
1.00	299.94	600.23	32.88	1.00	1.00	10.00	3.14
1.00	299.92	599.29	41.62	1.00	1.00	10.00	2.14
1.00	299.90	600.83	36.68	1.00	1.00	10.00	3.14
1.00	299.87	599.60	32.18	1.00	1.00	10.00	3.14
1.00	299.97	598.42	34.85	1.00	1.00	10.00	3.14
1.00	300.15	598.06	31.42	1.00	1.00	10.00	3.14
1.00	299.84	603.65	43.80	1.00	1.00	10.00	3.14
1.00	300.92	600.81	35.42	1.00	1.00	10.00	3.14
1.00	300.14	602.64	29.85	1.00	1.00	10.00	3.14
1.00	300.06	601.45	41.59	1.00	1.00	10.00	3.14
1.00	299.85	599.24	30.80	1.00	1.00	10.00	3.14
1.00	299.91	603.13	40.48	1.00	1.00	10.00	3.14
1.00	299.80	599.34	39.18	1.00	1.00	10.00	3.14
1.00	300.25	600.14	32.69	1.00	1.00	10.00	3.14
1.00	299.43	600.61	36.30	1.00	1.00	10.00	3.14
1.00	299.76	600.66	37.72	1.00	1.00	10.00	3.14
1.00	300.17	599.92	34.55	1.00	1.00	10.00	3.14
1.00	299.34	598.08	38.08	1.00	1.00	10.00	3.14
1.00	299.14905	600.8901	40.88848	1.00	1.00	10.00	3.14
1.00	299.99027	598.49989	36.59704	1.00	1.00	10.00	3.14
1.00	299.57588	600.35873	37.34846	1.00	1.00	10.00	2.14
1.00	300.13103	599.43407	34.513859	1.00	1.00	10.00	3.14
1.00	299.91403	599.71311	39.15785	1.00	1.00	10.00	3.14
1.00	299.96135	601.87282	35.051072	1.00	1.00	10.00	3.14

1.00	299.13392	598.23046	34.645323	1.00	1.00	10.00	3.14
1.00	299.91619	600.74935	33.086636	1.00	1.00	10.00	3.14
1.00	298.81351	600.00369	37.452526	1.00	1.00	10.00	3.14
1.00	300.51993	600.23343	33.96811	1.00	1.00	10.00	3.14
1.00	299.76233	600.17426	32.933705	1.00	1.00	10.00	3.14
1.00	300.46018	601.75828	33.594193	1.00	1.00	10.00	3.14
1.00	299.92285	600.16956	38.265685	1.00	1.00	10.00	3.14
1.00	299.80311	599.5234	35.536149	1.00	1.00	10.00	3.14
1.00	300.32663	600.91067	41.152979	1.00	1.00	10.00	3.14
1.00	299.69679	599.70121	36.005944	1.00	1.00	10.00	3.14
1.00	299.96856	599.10613	27.047746	1.00	1.00	10.00	3.14
1.00	299.90595	601.40052	25.934863	1.00	1.00	10.00	3.14
1.00	300.77016	597.97854	39.117793	1.00	1.00	10.00	3.14
1.00	299.82602	598.91251	40.531493	1.00	1.00	10.00	3.14
1.00	300.30125	600.21853	40.269511	1.00	1.00	10.00	3.14
1.00	299.76628	599.89019	31.493842	1.00	1.00	10.00	2.14
1.00	300.42787	599.75818	35.449283	1.00	1.00	10.00	3.14
1.00	301.12787	601.65624	32.03191	1.00	1.00	10.00	3.14
1.00	299.08553	602.29314	38.966842	1.00	1.00	10.00	3.14
1.00	300.37498	600.83177	37.338103	1.00	1.00	10.00	3.14
1.00	299.54036	599.59513	34.728384	1.00	1.00	10.00	3.14
1.00	299.89335	599.72689	40.845629	1.00	1.00	10.00	3.14
1.00	301.12616	599.38775	35.508286	1.00	1.00	10.00	3.14
1.00	300.14846	601.53449	46.142547	1.00	1.00	10.00	3.14
1.00	300.12372	599.74861	33.106116	1.00	1.00	10.00	3.14
1.00	299.26388	600.37814	35.280498	1.00	1.00	10.00	3.14
1.00	300.69579	601.39914	51.263381	1.00	1.00	10.00	3.14
1.00	300.51657	599.77555	35.833232	1.00	1.00	10.00	3.14
1.00	300.50139	600.29804	29.097847	1.00	1.00	10.00	3.14
1.00	300.48549	599.69441	41.932079	1.00	1.00	10.00	3.14
1.00	299.526	600.77	39.799134	1.00	1.00	10.00	3.14
1.00	300.12261	600.8498	28.222228	1.00	1.00	10.00	3.14
1.00	300.11047	597.85403	42.019918	1.00	1.00	10.00	3.14
1.00	300.11136	601.59752	31.14531	1.00	1.00	10.00	3.14
1.00	299.42283	600.00651	36.819008	1.00	1.00	10.00	2.14
1.00	299.95472	599.25951	35.049088	1.00	1.00	10.00	3.14
1.00	299.79253	600.23737	27.7352	1.00	1.00	10.00	3.14
1.00	299.57433	601.44926	38.43471	1.00	1.00	10.00	3.14
1.00	299.91367	600.47478	36.635695	1.00	1.00	10.00	3.14
1.00	299.60169	599.86152	35.917144	1.00	1.00	10.00	3.14
1.00	299.68214	600.12456	39.417573	1.00	1.00	10.00	3.14
1.00	299.37749	599.87337	41.456983	1.00	1.00	10.00	3.14
1.00	300.62773	599.78492	37.505974	1.00	1.00	10.00	3.14
1.00	299.68672	600.14875	30.203206	1.00	1.00	10.00	3.14
1.00	299.94873	600.12911	37.013191	1.00	1.00	10.00	3.14

1.00	300.39878	600.12775	33.995395	1.00	1.00	10.00	3.14
1.00	300.7864	601.16113	42.028301	1.00	1.00	10.00	3.14
1.00	300.1147	601.39121	31.703692	1.00	1.00	10.00	3.14
1.00	300.48275	599.96522	42.756764	1.00	1.00	10.00	3.14
1.00	300.82664	599.23535	36.547592	1.00	1.00	10.00	3.14
1.00	299.48377	600.84702	38.295507	1.00	1.00	10.00	3.14
1.00	299.721	601.48116	35.619869	1.00	1.00	10.00	3.14
1.00	300.14572	598.33745	34.632132	1.00	1.00	10.00	3.14
1.00	299.35524	600.36747	34.002679	1.00	1.00	10.00	2.14
1.00	300.04583	600.06382	30.692809	1.00	1.00	10.00	3.14
1.00	299.95905	599.71642	26.128672	1.00	1.00	10.00	3.14
1.00	301.0603	598.72575	23.623646	1.00	1.00	10.00	3.14
1.00	299.86825	602.54394	31.727881	1.00	1.00	10.00	3.14
1.00	299.78718	598.88693	28.97193	1.00	1.00	10.00	3.14
1.00	300.01945	599.82993	34.358809	1.00	1.00	10.00	3.14
1.00	300.8938	599.78204	36.637097	1.00	1.00	10.00	3.14
1.00	299.64541	599.64709	32.631581	1.00	1.00	10.00	3.14
1.00	300.28264	599.27353	41.211161	1.00	1.00	10.00	3.14
1.00	300.0808	600.23252	32.728749	1.00	1.00	10.00	3.14
1.00	300.60278	599.16873	44.544777	1.00	1.00	10.00	3.14
1.00	299.09665	601.83815	23.059592	1.00	1.00	10.00	3.14
1.00	299.88345	601.41927	26.041416	1.00	1.00	10.00	3.14
1.00	300.60196	598.16442	25.585281	1.00	1.00	10.00	3.14
1.00	299.85314	601.36075	29.777213	1.00	1.00	10.00	3.14
1.00	300.74389	600.75948	27.290975	1.00	1.00	10.00	3.14
1.00	300.62891	599.47266	38.634265	1.00	1.00	10.00	3.14
1.00	299.21569	599.40304	32.417977	1.00	1.00	10.00	3.14
1.00	299.7072	600.56385	34.317121	1.00	1.00	10.00	3.14
1.00	300.53022	600.53226	35.253774	1.00	1.00	10.00	3.14
1.00	300.47709	601.72984	41.258631	1.00	1.00	10.00	3.14

Appendix 2a, Page 2:

DIA	COR. RATE	T	TI	R	S	GX	vio
25.87	0.10	35.00	0.00	3684116.9	2496546.24	1187571	0
24.34	0.10	35.00	0.00	3913134.1	3001729.38	911405	0
27.64	0.10	35.00	0.00	4634803	3573725.08	1061078	0
21.45	0.10	35.00	0.00	3960749.5	2893891.8	1066858	0
22.75	0.10	35.00	0.00	3678456.3	2283700.5	1394756	0
23.28	0.10	35.00	0.00	3975209.4	2452015.06	1523194	0
24.47	0.10	35.00	0.00	3783657.2	3512544.16	271113	0
24.67	0.10	35.00	0.00	4957217.6	4245523.74	711694	0
24.50	0.10	35.00	0.00	4177396.1	4934790.85	-757395	1

25.18	0.10	35.00	0.00	3746095.3	3071078.28	675017	0
26.62	0.10	35.00	0.00	4951916.5	4361741.68	590175	0
25.13	0.10	35.00	0.00	3788216.3	4660232.14	-872016	1
22.44	0.10	35.00	0.00	4405444.1	4212573.4	192871	0
25.71	0.10	35.00	0.00	4610722	3659886.3	950836	0
26.04	0.10	35.00	0.00	4104407.8	5217420.23	-1113012	1
21.55	0.10	35.00	0.00	3917029.6	4067930.38	-150901	1
23.86	0.10	35.00	0.00	4292972	2366737.89	1926234	0
24.51	0.10	35.00	0.00	4069866.8	5253924.47	-1184058	1
28.54	0.10	35.00	0.00	4884205.5	5441599.5	-557394	1
19.29909	0.10	35.00	0.00	4165778	4949675.2	-783897	1
24.44067	0.10	35.00	0.00	4227356.1	4701664.62	-474308	1
26.58257	0.10	35.00	0.00	4173179.3	4364155.09	-190976	1
25.29327	0.10	35.00	0.00	4167651.7	4291341.83	-123690	1
20.48804	0.10	35.00	0.00	4087114.6	4104283.95	-17169	1
20.72149	0.10	35.00	0.00	3747956.6	4332738.81	-584782	1
25.25735	0.10	35.00	0.00	4148013.1	4105768.97	42244	0
26.56483	0.10	35.00	0.00	4171008	3963837.93	207170	0
23.84215	0.10	35.00	0.00	4259825.6	3225243.65	1034582	0
28.32896	0.10	35.00	0.00	4508555.1	2532388.59	1976167	0
22.01046	0.10	35.00	0.00	3662922.8	3273764.68	389158	0
28.02462	0.10	35.00	0.00	4414756.6	2988235.75	1426521	0
24.10894	0.10	35.00	0.00	4357778.9	4163864.87	193914	0
23.2025	0.10	35.00	0.00	4024498.2	3554877.01	469621	0
21.20248	0.10	35.00	0.00	4347655.3	2530176.18	1817479	0
29.22502	0.10	35.00	0.00	4827834.8	3371704.96	1456130	0
22.12067	0.10	35.00	0.00	3140658.1	3657612.15	-516954	1
27.65272	0.10	35.00	0.00	3669566.9	3987907.42	-318340	1
26.49547	0.10	35.00	0.00	4700227	2429159.01	2271068	0
25.35887	0.10	35.00	0.00	4692656.5	3301479.71	1391177	0
26.41617	0.10	35.00	0.00	4830821.7	2905681.1	1925141	0
25.78051	0.10	35.00	0.00	3584022.3	3152270.91	431751	0
24.57809	0.10	35.00	0.00	4164890.9	5534780.66	-1369890	1
25.09982	0.10	35.00	0.00	3917152	2627807	1289345	0
14.28357	0.10	35.00	0.00	3675306.5	3595217.53	80089	0
26.83155	0.10	35.00	0.00	4606365.5	4336165.42	270200	0
26.88078	0.10	35.00	0.00	4345442.8	4073357	272086	0
23.1984	0.10	35.00	0.00	4514734.2	5185913.14	-671179	1
23.91473	0.10	35.00	0.00	4096792.2	5201815.61	-1105023	1
24.10485	0.10	35.00	0.00	5094981.4	6025052.21	-930071	1
24.1491	0.10	35.00	0.00	3905192.2	5086403.9	-1181212	1
25.83226	0.10	35.00	0.00	4310485.5	2646118.08	1664367	0
24.87329	0.10	35.00	0.00	5652470.5	4435809.87	1216661	0
28.0359	0.10	35.00	0.00	4617463.4	2727119.71	1890344	0
27.27716	0.10	35.00	0.00	3917460.9	2574177.65	1343283	0

22.68705	0.10	35.00	0.00	4561873.3	5050313.5	-488440	1
24.7783	0.10	35.00	0.00	4583379.3	5113937.36	-530558	1
22.90167	0.10	35.00	0.00	3341056.2	3650326.72	-309271	1
24.72091	0.10	35.00	0.00	4755418.4	3548495.4	1206923	0
24.91868	0.10	35.00	0.00	3835197.1	4208006.78	-372810	1
22.54691	0.10	35.00	0.00	3820123.7	2822167.99	997956	0
26.37829	0.10	35.00	0.00	4320579.6	3123859.38	1196720	0
24.22354	0.10	35.00	0.00	3437169.5	2833847.21	603322	0
25.46656	0.10	35.00	0.00	4546671.1	4404453.83	142217	0
26.76509	0.10	35.00	0.00	4520468.2	3438789.67	1081679	0
27.32452	0.10	35.00	0.00	4503962	4712560.35	-208598	1
25.73891	0.10	35.00	0.00	4660276.8	2791420.09	1868857	0
24.45234	0.10	35.00	0.00	4677081	3182209.67	1494871	0
24.64997	0.10	35.00	0.00	4372792.8	3976410.52	396382	0
26.80726	0.10	35.00	0.00	3920381	2536022.2	1384359	0
27.81454	0.10	35.00	0.00	4694368.3	3660792.91	1033575	0
29.09424	0.10	35.00	0.00	4600828.7	3750273.81	850555	0
26.48492	0.10	35.00	0.00	5017939.6	4044521.51	973418	0
26.01853	0.10	35.00	0.00	3988024.4	3023903.34	964121	0
22.75252	0.10	35.00	0.00	4625691.4	4374214.77	251477	0
26.33109	0.10	35.00	0.00	4466850.4	4110366.38	356484	0
27.82806	0.10	35.00	0.00	4792292.7	2909454.28	1882838	0
26.48778	0.10	35.00	0.00	4401124.5	4312735.88	88389	0
21.40768	0.10	35.00	0.00	3751614.2	2779021.9	972592	0
27.04612	0.10	35.00	0.00	3915995.1	4420540.71	-504546	1
23.94467	0.10	35.00	0.00	3662400	5705541.3	-2043141	1
30.24557	0.10	35.00	0.00	4048750.6	4575023.29	-526273	1
23.00372	0.10	35.00	0.00	2940255.6	3037786.46	-97531	1
25.0302	0.10	35.00	0.00	3888217.1	3388823	499394	0
25.96391	0.10	35.00	0.00	3742617.9	2743457.16	999161	0
30.68005	0.10	35.00	0.00	4866026.1	3900501.13	965525	0
24.55621	0.10	35.00	0.00	4271365.9	1769442.85	2501923	0
24.75026	0.10	35.00	0.00	3919879.4	3984446.68	-64567	1
25.99002	0.10	35.00	0.00	4833654	4169802.94	663851	0
23.28671	0.10	35.00	0.00	3761034.8	3021164.98	739870	0
28.72663	0.10	35.00	0.00	5490916.9	3623729.41	1867188	0
24.02939	0.10	35.00	0.00	2975315.2	3426329.55	-451014	1
29.65813	0.10	35.00	0.00	3964709.5	2928956.08	1035753	0
25.0434	0.10	35.00	0.00	3304785.1	4108838.4	-804053	1
23.33531	0.10	35.00	0.00	3510193.4	5115439.46	-1605246	1
25.83213	0.10	35.00	0.00	3572410.6	3024988.34	547422	0
21.26105	0.10	35.00	0.00	4129505.5	5239456.53	-1109951	1
18.17737	0.10	35.00	0.00	3297274.7	4101354.79	-804080	1
23.95129	0.10	35.00	0.00	4008514.3	4413728.87	-405215	1
29.65694	0.10	35.00	0.00	4824621.7	2899063.03	1925559	0

24.40961	0.10	35.00	0.00	4711389.2	2442778.14	2268611	0
							35

Appendix 2a, Page 3

FSC	GAMMAD	GAMMAL	DL	LL	AS		
						Corr Rate	
400.63	1.35	1.50	774122.86	967653.58		=	0.1
403.48	1.35	1.50	930768.8	1163461.00	2363.08	KC =	1
392.09	1.35	1.50	1108131.8	1385164.76	2282.13	KPI =	1
400.22	1.35	1.50	897330.79	1121663.49	1640.00	PIEFF =	1
403.03	1.35	1.50	708124.19	885155.23	1948.47	NBARS =	10
407.38	1.35	1.50	760314.75	950393.43	2080.50	T =	35
402.15	1.35	1.50	1089161	1361451.22	2395.48	TI =	0
405.22	1.35	1.50	1316441.5	1645551.84	2451.32		
405.91	1.35	1.50	1530167.7	1912709.63	2403.20		
403.32	1.35	1.50	952272.33	1190340.42	2594.84	ALPHA	0.8
397.03	1.35	1.50	1352478	1690597.55	3020.60		
395.77	1.35	1.50	1445033.2	1806291.53	2579.07	TRIALS	100
						FAIL	
397.77	1.35	1.50	1306224.3	1632780.39	1870.48	CASES	35
396.83	1.35	1.50	1134848.5	1418560.58	2748.59	FAILURE	0.35
407.20	1.35	1.50	1617804.7	2022255.90	2846.38	SAFETY	0.65
392.72	1.35	1.50	1261373.8	1576717.20	1661.57		
402.00	1.35	1.50	733872.21	917340.27	2232.16		
398.28	1.35	1.50	1629123.9	2036404.83	2407.66		
405.38	1.35	1.50	1687317.7	2109147.09	3640.77		
413.0668	1.35	1.50	1534783	1918478.76	1188.21		
394.24119	1.35	1.50	1457880.5	1822350.63	2389.31		
396.66689	1.35	1.50	1353226.4	1691532.98	2053.52		
404.64306	1.35	1.50	1330648.6	1663310.79	2626.95		
396.04438	1.35	1.50	1272646.2	1590807.73	1428.13		
395.0773	1.35	1.50	1343484.9	1679356.13	1477.99		
400.55262	1.35	1.50	1273106.7	1591383.32	2616.65		
396.1353	1.35	1.50	1229097	1536371.29	3004.84		
405.26443	1.35	1.50	1000075.5	1250094.44	2226.72		
404.61263	1.35	1.50	785236.77	981545.96	3571.16		
395.98122	1.35	1.50	1015120.8	1268901.04	1768.71		
397.05443	1.35	1.50	926584.73	1158230.91	3469.97		
397.67276	1.35	1.50	1291120.9	1613901.11	2297.82		
403.18622	1.35	1.50	1102287.4	1377859.31	2060.79		
400.54092	1.35	1.50	784550.75	980688.44	1583.43		
410.6201	1.35	1.50	1045489.9	1306862.39	3877.52		
395.72605	1.35	1.50	1134143.3	1417679.13	1794.78		
397.43002	1.35	1.50	1236560.4	1545700.55	3348.30		
396.3297	1.35	1.50	753227.6	941534.50	2983.57		

397.93793	1.35	1.50	1023714.6	1279643.30	2647.51
405.77784	1.35	1.50	900986.39	1126232.99	2961.24
398.30748	1.35	1.50	977448.34	1221810.43	1888.75
400.39868	1.35	1.50	1716211.1	2145263.82	2425.56
394.85884	1.35	1.50	814823.88	1018529.85	2571.69
397.69524	1.35	1.50	1114796.1	1393495.17	416.45
400.69312	1.35	1.50	1344547.4	1680684.27	3087.33
395.39496	1.35	1.50	1263056.4	1578820.54	3102.68
408.59739	1.35	1.50	1608035.1	2010043.85	2059.75
397.3034	1.35	1.50	1612966.1	2016207.60	2245.95
404.69471	1.35	1.50	1868233.2	2335291.55	2296.72
400.95918	1.35	1.50	1577179.5	1971474.38	2308.62
409.84966	1.35	1.50	820501.73	1025627.16	2784.03
405.66051	1.35	1.50	1375444.9	1719306.15	2507.72
399.61103	1.35	1.50	845618.51	1057023.14	3473.70
400.59543	1.35	1.50	798194.62	997743.28	3227.63
405.74693	1.35	1.50	1565988.7	1957485.85	1931.76
404.06	1.35	1.50	1585717	1982146.26	2481.13
401.22338	1.35	1.50	1131884.3	1414855.32	1984.98
399.62706	1.35	1.50	1100308.7	1375385.81	2466.71
405.86124	1.35	1.50	1304808.3	1631010.38	2522.08
396.1502	1.35	1.50	875090.85	1093863.56	1294.34
397.08366	1.35	1.50	968638.57	1210798.21	2947.82
404.40519	1.35	1.50	878712.31	1098390.39	2328.71
404.97882	1.35	1.50	1365722.1	1707152.65	2676.96
398.34602	1.35	1.50	1066291.4	1332864.21	3066.67
393.63683	1.35	1.50	1461259	1826573.78	3242.72
404.75864	1.35	1.50	865556.62	1081945.77	2756.50
399.19979	1.35	1.50	986731.68	1233414.60	2390.98
405.40882	1.35	1.50	1232995.5	1541244.39	2445.44
391.02182	1.35	1.50	786363.47	982954.34	3079.77
400.77744	1.35	1.50	1135129.6	1418911.98	3400.97
400.96958	1.35	1.50	1162875.6	1453594.50	3832.02
408.72333	1.35	1.50	1254115.2	1567643.99	2980.35
396.91168	1.35	1.50	937644.45	1172055.56	2839.38
396.12311	1.35	1.50	1356345.7	1695432.08	1947.91
399.76719	1.35	1.50	1274532.2	1593165.26	2933.48
395.48156	1.35	1.50	902156.37	1127695.46	3405.39
399.04904	1.35	1.50	1337282.4	1671603.05	2983.12
393.63944	1.35	1.50	861712.22	1077140.27	1630.55
399.86271	1.35	1.50	1370710.3	1713387.87	2151.89
399.01024	1.35	1.50	1769160.1	2211450.12	2253.91
400.44395	1.35	1.50	1418611.9	1773264.84	4241.80
403.44727	1.35	1.50	941949.29	1177436.61	2010.53
400.4244	1.35	1.50	1050797.8	1313497.29	2551.94

404.45938	1.35	1.50	850684.39	1063355.49	2823.10
403.10561	1.35	1.50	1209457.7	1511822.14	4401.85
399.00486	1.35	1.50	548664.45	685830.56	2419.53
399.5585	1.35	1.50	1235487.3	1544359.18	2473.31
397.63336	1.35	1.50	1292962.2	1616202.69	2830.87
390.68605	1.35	1.50	936795.34	1170994.18	2082.27
399.23651	1.35	1.50	1123637	1404546.28	3705.57
395.28319	1.35	1.50	1062427.8	1328034.71	2276.50
401.06776	1.35	1.50	908203.44	1135254.29	4030.12
393.0648	1.35	1.50	1274058.4	1592573.02	2555.68
394.07849	1.35	1.50	1586182.8	1982728.47	2094.71
397.6356	1.35	1.50	937980.88	1172476.10	2784.00
406.00649	1.35	1.50	1624637.7	2030797.11	1596.51
397.8464	1.35	1.50	1271737.9	1589672.40	980.73
407.90039	1.35	1.50	1368598.1	1710747.62	2255.67
407.81115	1.35	1.50	898934.27	1123667.84	4029.70
412.51121	1.35	1.50	757450.59	946813.23	2379.29

Appendix 2a, Page 4:

LL	DL
967.65	774.12
1163.46	930.77
1385.16	1108.13
1121.66	897.33
885.16	708.12
950.39	760.31
1361.45	1089.16
1645.55	1316.44
1912.71	1530.17
1190.34	952.27
1690.60	1352.48
1806.29	1445.03
1632.78	1306.22
1418.56	1134.85
2022.26	1617.80
1576.72	1261.37
917.34	733.87
2036.40	1629.12
2109.15	1687.32
1918.48	1534.78
1822.35	1457.88
1691.53	1353.23
1663.31	1330.65

1590.81	1272.65
1679.36	1343.48
1591.38	1273.11
1536.37	1229.10
1250.09	1000.08
981.55	785.24
1268.90	1015.12
1158.23	926.58
1613.90	1291.12
1377.86	1102.29
980.69	784.55
1306.86	1045.49
1417.68	1134.14
1545.70	1236.56
941.53	753.23
1279.64	1023.71
1126.23	900.99
1221.81	977.45
2145.26	1716.21
1018.53	814.82
1393.50	1114.80
1680.68	1344.55
1578.82	1263.06
2010.04	1608.04
2016.21	1612.97
2335.29	1868.23
1971.47	1577.18
1025.63	820.50
1719.31	1375.44
1057.02	845.62
997.74	798.19
1957.49	1565.99
1982.15	1585.72
1414.86	1131.88
1375.39	1100.31
1631.01	1304.81
1093.86	875.09
1210.80	968.64
1098.39	878.71
1707.15	1365.72
1332.86	1066.29
1826.57	1461.26
1081.95	865.56
1233.41	986.73
1541.24	1233.00

982.95	786.36
1418.91	1135.13
1453.59	1162.88
1567.64	1254.12
1172.06	937.64
1695.43	1356.35
1593.17	1274.53
1127.70	902.16
1671.60	1337.28
1077.14	861.71
1713.39	1370.71
2211.45	1769.16
1773.26	1418.61
1177.44	941.95
1313.50	1050.80
1063.36	850.68
1511.82	1209.46
685.83	548.66
1544.36	1235.49
1616.20	1292.96
1170.99	936.80
1404.55	1123.64
1328.03	1062.43
1135.25	908.20
1592.57	1274.06
1982.73	1586.18
1172.48	937.98
2030.80	1624.64
1589.67	1271.74
1710.75	1368.60
1123.67	898.93
946.81	757.45

Appendic 2b: Failure due to Cracking and Spalling of the Concrete

Appendix 2b, page 1:

bet	v	wi	alpha1	t	a1	a2	c
9.49	0.40	0.59	10.70	20.00	85.38	7.34	41.83
10.87	0.40	0.37	9.57	20.00	75.32	7.28	41.86
7.32	0.40	0.44	11.13	20.00	78.66	7.34	40.22
5.37	0.40	0.49	9.01	20.00	61.50	7.33	42.49
7.36	0.40	0.51	18.98	20.00	73.23	7.27	39.90
6.63	0.40	0.47	10.50	20.00	72.43	7.28	40.54
8.16	0.40	0.43	11.43	20.00	70.18	7.30	43.60

7.44	0.40	0.30	14.67	20.00	72.46	7.30	40.16
10.99	0.40	0.57	8.62	20.00	67.77	7.25	43.51
12.11	0.40	0.63	7.78	20.00	69.60	7.28	40.08
10.27	0.40	0.64	7.63	20.00	73.42	7.38	43.29
2.17	0.40	0.58	14.62	20.00	71.58	7.34	42.27
8.82	0.40	0.62	11.46	20.00	78.47	7.34	44.23
7.64	0.40	0.66	6.46	20.00	72.62	7.30	41.74
8.22	0.40	0.64	6.06	20.00	82.06	7.24	39.35
11.93	0.40	0.50	19.25	20.00	73.45	7.17	39.08
11.10	0.40	0.58	5.44	20.00	71.81	7.31	38.67
9.97	0.40	0.34	11.64	20.00	65.18	7.42	39.95
12.66	0.40	0.45	2.62	20.00	75.85	7.23	42.91
12.511349	0.40	0.4494046	3.62	20.00	65.79	7.31	38.48695
11.312499	0.40	0.5202975	9.75	20.00	71.34	7.30	40.56496
6.1227673	0.40	0.5160853	13.57	20.00	77.18	7.29	40.74469
8.648171	0.40	0.2822202	5.16	20.00	68.67	7.33	41.62449
9.2694418	0.40	0.5214753	1.98	20.00	75.51	7.29	41.15342
11.264796	0.40	0.3379094	4.32	20.00	78.73	7.31	41.59791
6.8621577	0.40	0.5884971	12.99	20.00	70.22	7.26	40.58511
8.5990903	0.40	0.6447798	4.40	20.00	71.75	7.34	43.52834
4.6649369	0.40	0.5495201	9.88	20.00	69.56	7.38	43.00861
11.286226	0.40	0.4970364	12.30	20.00	70.94	7.29	40.89068
10.493783	0.40	0.5929831	19.36	20.00	72.69	7.31	43.20988
6.0714594	0.40	0.6135811	3.89	20.00	65.31	7.30	43.36068
9.6467206	0.40	0.4894257	9.00	20.00	68.83	7.32	41.72701
9.8266927	0.40	0.309556	9.19	20.00	73.08	7.37	40.34007
13.197813	0.40	0.4785553	10.15	20.00	77.07	7.32	40.40711
9.3545078	0.40	0.4794541	16.08	20.00	74.11	7.35	41.02053
13.012766	0.40	0.4672833	11.62	20.00	81.72	7.34	41.45959
8.8175653	0.40	0.5460657	11.28	20.00	86.81	7.41	43.3235
9.2719531	0.40	0.5514148	7.22	20.00	82.26	7.23	42.19347
8.0271132	0.40	0.5670181	13.45	20.00	71.23	7.33	40.46958
4.7365639	0.40	0.5367615	17.78	20.00	70.34	7.33	40.26758
12.648921	0.40	0.4983095	-3.78	20.00	76.79	7.44	40.22663
12.392501	0.40	0.6877945	6.03	20.00	73.15	7.26	40.82209
6.9931323	0.40	0.3815519	15.82	20.00	72.33	7.23	41.98722
14.65413	0.40	0.4107758	4.98	20.00	77.77	7.26	40.4361
6.452324	0.40	0.5710302	17.75	20.00	69.76	7.24	42.21414
10.936438	0.40	0.4340272	7.54	20.00	79.29	7.28	41.90194
9.0834314	0.40	0.6197503	7.69	20.00	81.81	7.25	41.50783
13.218812	0.40	0.3065964	15.71	20.00	71.30	7.36	39.07798
11.000885	0.40	0.534641	12.39	20.00	82.96	7.25	44.60792
8.5911161	0.40	0.4655133	6.46	20.00	80.85	7.29	41.51107
10.882002	0.40	0.4977044	14.61	20.00	73.08	7.22	40.78951
12.345511	0.40	0.3381159	13.98	20.00	75.33	7.35	41.67241

9.7480974	0.40	0.494227	5.64	20.00	65.75	7.24	42.9489
8.9308378	0.40	0.6800479	12.62	20.00	77.67	7.26	39.41195
10.173497	0.40	0.5004381	13.26	20.00	70.40	7.22	40.72652
10.227392	0.40	0.632327	5.21	20.00	70.61	7.31	41.92301
7.5677754	0.40	0.4655449	0.67	20.00	73.11	7.34	39.87193
6.73498	0.40	0.3692542	15.94	20.00	67.03	7.35	38.94069
10.169158	0.40	0.3828569	6.26	20.00	82.35	7.33	41.32799
11.455511	0.40	0.8474899	10.96	20.00	78.44	7.25	42.97848
14.339271	0.40	0.181954	2.09	20.00	66.39	7.33	43.69412
4.5283031	0.40	0.4519816	13.29	20.00	71.45	7.26	39.85221
8.145619	0.40	0.2822295	8.95	20.00	76.11	7.34	41.12558
10.441082	0.40	0.4590498	0.42	20.00	81.42	7.30	40.83049
13.159959	0.40	0.3252199	6.16	20.00	76.85	7.34	41.16451
8.8729779	0.40	0.2910623	16.92	20.00	77.40	7.26	39.28388
4.0247986	0.40	0.476602	17.38	20.00	77.67	7.32	39.24023
5.2395092	0.40	0.6147925	1.76	20.00	74.82	7.37	40.07533
6.5010339	0.40	0.4927709	4.86	20.00	76.69	7.24	40.86925
10.931051	0.40	0.6270053	16.26	20.00	81.92	7.34	40.11906
11.262931	0.40	0.5751871	11.35	20.00	77.00	7.39	40.92532
7.915338	0.40	0.3348429	8.51	20.00	78.15	7.23	41.92907
11.242087	0.40	0.3510762	7.20	20.00	77.23	7.29	39.34242
10.213736	0.40	0.5551486	10.07	20.00	72.93	7.34	43.09194
12.651365	0.40	0.3974431	14.64	20.00	74.03	7.25	43.05374
12.225996	0.40	0.4185483	2.35	20.00	71.43	7.39	41.73541
8.7924911	0.40	0.4682585	11.81	20.00	66.86	7.31	41.2865
7.0005303	0.40	0.6040937	5.16	20.00	76.26	7.26	41.21706
10.86868	0.40	0.5678949	11.75	20.00	69.91	7.48	41.98722
5.9295409	0.40	0.4995521	4.76	20.00	70.51	7.36	42.77824
10.539273	0.40	0.4262347	8.65	20.00	71.34	7.33	42.53429
4.0864509	0.40	0.4317759	6.20	20.00	78.73	7.23	39.07903
8.2595601	0.40	0.2919191	3.95	20.00	69.34	7.34	41.21847
4.1622665	0.40	0.5171891	7.12	20.00	76.69	7.29	41.53777
10.99141	0.40	0.4910533	8.35	20.00	77.62	7.33	42.34413
7.2611088	0.40	0.3843822	11.10	20.00	61.27	7.26	43.02914
9.3231336	0.40	0.6092979	8.02	20.00	75.88	7.23	42.75945
9.0898451	0.40	0.6265735	4.23	20.00	72.86	7.33	41.59895
8.8412931	0.40	0.6501233	12.26	20.00	68.03	7.37	40.15095
6.7116541	0.40	0.4835869	15.99	20.00	71.25	7.23	41.63459
15.100962	0.40	0.528186	8.47	20.00	68.79	7.31	40.95675
10.287774	0.40	0.543893	8.11	20.00	76.88	7.31	41.57838
14.160871	0.40	0.4429508	6.19	20.00	73.09	7.23	40.54911
12.915918	0.40	0.4824924	5.22	20.00	74.10	7.24	42.06882
9.833586	0.40	0.6815556	3.93	20.00	78.17	7.37	38.20845
6.0726299	0.40	0.6252367	6.85	20.00	69.36	7.37	37.55999
10.962831	0.40	0.3877942	9.91	20.00	81.60	7.30	40.27643

10.386924	0.40	0.3752233	6.74	20.00	81.70	7.30	41.11864
8.7275987	0.40	0.4466108	8.82	20.00	80.19	7.24	42.11732
11.651288	0.40	0.4328123	10.82	20.00	84.84	7.22	40.74826

Appendix 2b, page 2:

pi1	a3	ftspl	R	S	GX	vio
25.08	-15.46	4.61	0.33	-265.769	266	0
24.60	-19.86	4.66	0.40	-464.93316	465	0
25.13	-17.44	4.15	0.24	-246.22022	246	0
25.07	-15.02	4.26	0.34	-99.106216	99	0
25.09	-17.41	4.47	0.39	72.854657	-72	1
25.01	-28.30	4.03	0.31	-194.21554	195	0
24.82	-14.68	4.46	0.26	-190.52264	191	0
24.87	-20.68	4.32	0.37	-243.23292	244	0
24.75	-17.51	4.34	0.30	-244.13344	244	0
24.93	-14.33	4.57	0.29	-281.38965	282	0
25.23	-14.19	4.01	0.32	-250.81171	251	0
25.05	-18.35	4.50	0.34	3.09777078	-3	1
25.05	-19.85	4.45	0.32	-147.84241	148	0
24.79	-15.60	4.69	0.21	-246.74177	247	0
24.81	-19.58	4.12	0.26	-377.09351	377	0
24.78	-18.14	4.54	0.23	100.148236	-100	1
25.15	-13.57	4.34	0.33	-423.77918	424	0
25.18	-20.12	4.37	0.27	-289.1393	289	0
24.87	-14.84	4.36	0.28	-743.64833	744	0
24.23	-15.46	4.22	0.23	-574.12335	574	0
24.61	-17.08	4.91	0.35	-291.45329	292	0
25.51	-20.06	4.40	0.27	-100.53518	101	0
25.45	-17.99	4.35	0.31	-443.0343	443	0
24.72	-18.73	4.66	0.28	-578.97822	579	0
25.21	-15.36	4.78	0.24	-684.26055	684	0
25.16	-20.52	4.55	0.34	-32.433544	33	0
25.29	-16.75	4.49	0.29	-366.55899	367	0
25.33	-16.50	4.51	0.23	-91.675515	92	0
24.65	-17.38	4.63	0.20	-188.51006	189	0
24.77	-26.11	4.54	0.42	236.657084	-236	1
24.62	-11.86	4.10	0.31	-200.45842	201	0
25.39	-21.62	4.21	0.18	-279.11958	279	0
24.60	-18.62	4.42	0.33	-443.76053	444	0
25.39	-15.31	4.07	0.25	-398.35587	399	0
25.03	-19.09	4.40	0.39	-68.339067	69	0
24.86	-20.23	4.48	0.32	-437.7826	438	0

25.07	-21.29	4.66	0.37	-292.92367	293	0
25.06	-13.72	4.26	0.44	-382.90218	383	0
25.34	-12.48	4.73	0.20	-11.519198	12	0
24.98	-22.67	4.51	0.38	46.4692138	-46	1
25.30	-17.02	4.74	0.29	-1093.4692	1094	0
24.89	-19.06	4.33	0.30	-431.29364	432	0
25.25	-21.06	4.34	0.30	-135.98521	136	0
24.93	-14.92	4.75	0.28	-805.84704	806	0
25.22	-16.82	4.46	0.32	112.817355	-112	1
24.61	-14.96	4.55	0.37	-504.10023	504	0
25.06	-16.85	4.22	0.22	-337.49465	338	0
25.10	-22.21	4.49	0.24	-382.07957	382	0
24.85	-13.56	4.44	0.35	-229.05969	229	0
25.11	-16.28	4.35	0.33	-430.91156	431	0
24.93	-18.31	4.45	0.31	-105.76495	106	0
24.99	-21.38	4.27	0.32	-406.04477	406	0
24.76	-11.85	4.16	0.40	-300.19803	301	0
25.16	-19.00	4.30	0.25	-35.150415	35	0
25.04	-16.54	4.64	0.28	-118.18393	118	0
25.42	-15.71	4.60	0.44	-385.53097	386	0
25.25	-13.11	4.73	0.38	-473.98069	474	0
24.86	-17.57	4.52	0.29	-98.959474	99	0
25.21	-19.60	4.00	0.27	-584.63129	585	0
24.63	-15.35	4.27	0.35	40.300083	-40	1
24.75	-24.00	4.27	0.28	-849.24774	850	0
25.21	-19.03	4.34	0.40	-83.126856	84	0
24.93	-20.67	4.37	0.32	-417.69236	418	0
24.77	-17.27	4.23	0.35	-769.67779	770	0
25.24	-17.59	4.03	0.38	-713.4104	714	0
25.01	-15.69	4.43	0.21	-280.32566	281	0
24.87	-14.78	4.26	0.27	-15.462554	16	0
25.07	-16.57	4.54	0.32	-315.82994	316	0
24.88	-18.85	4.47	0.33	-341.61582	342	0
24.67	-20.22	4.46	0.18	44.932178	-45	1
25.07	-12.35	4.76	0.40	-178.30096	179	0
24.61	-13.38	4.48	0.32	-370.17285	370	0
25.19	-19.24	4.34	0.28	-585.60434	586	0
24.97	-9.07	4.48	0.31	-82.04011	82	0
24.99	-19.65	4.36	0.18	-282.30747	282	0
25.32	-16.89	4.32	0.31	-698.18219	698	0
25.34	-17.86	4.31	0.26	-147.34716	148	0
25.15	-17.92	4.13	0.18	-316.53075	317	0
24.94	-17.73	4.42	0.20	-115.79465	116	0
25.10	-18.43	4.68	0.29	-274.67659	275	0
24.92	-19.35	4.47	0.20	-387.4413	388	0

24.91	-21.50	4.58	0.22	-218.48649	219	0
25.28	-16.57	4.46	0.27	-445.02711	445	0
24.71	-14.26	4.58	0.33	-165.50101	166	0
25.13	-14.52	4.38	0.23	-403.66606	404	0
24.97	-13.29	4.83	0.34	-139.26343	140	0
24.95	-20.09	4.43	0.26	-297.84732	298	0
24.83	-16.19	4.18	0.33	-405.03046	405	0
24.74	-20.39	4.23	0.34	4.77877739	-4	1
25.35	-25.42	4.22	0.19	-38.42282	39	0
25.08	-18.37	4.32	0.29	-414.84677	415	0
25.06	-22.36	4.33	0.33	-384.21921	385	0
24.98	-13.43	4.72	0.30	-616.39348	617	0
24.68	-13.31	4.24	0.35	-572.85922	573	0
24.82	-16.42	4.42	0.38	-499.75288	500	0
25.22	-16.27	4.35	0.36	-176.20323	177	0
25.05	-18.22	4.27	0.33	-496.38258	497	0
25.22	-19.21	4.38	0.35	-585.7358	586	0
25.09	-14.91	4.25	0.23	-355.31158	356	0
25.14	-15.40	4.43	0.38	-472.37587	473	0

Appendix 2b, page 3:

Corr Rate =	0.4
time	20
TRIALS	100
FAIL CASES	9
FAILURE	0.09
SAFETY	0.91