REHABILITATION OF DETERIORATED REINFORCED CONCRETE MEMBERS USING ADVANCED COMPOSITE MATERIALS

A CASE STUDY OF A DETERIORATED 8-STOREY BUILDING IN THE CITY OF ABU DHABI IN THE UNITED ARAB EMIRATES

إعادة تأهيل المنشآت الخرسانية باستخدام المواد المركبة المستحدثة/المتطورة الدقيقة

دراسة لحالة مبنى مهترئ مكون من طابق أرضي و ثمانية في مدينة أبوظبي في دولة الإمارات العربية المتحدة

by

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A dissertation submitted in fulfilment of the requirements for the degree of MSc STRUCTURAL ENGINEERING at The British University in Dubai

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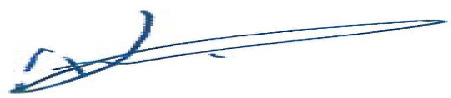

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Abstract

The deterioration of reinforced concrete in building structures due to factors such as aging, reinforcement corrosion, humidity and oxidation, and freeze-thaw events, had imposed a great deal of stresses on these structures. In addition, unfortunate errors or omissions in preliminary designs performed by designers have motivated the researchers on finding a more durable and sustainable material that can be used in repairing and rehabilitation of deteriorated structural elements. Due to the scarcity of raw materials, the rising expenses in production, durability and ecological concerns, and the necessity to attain a high strength to weight ratio material dictated the expansion of research to discover new materials that acquire sufficient engineering properties to meet the rising demands of the construction industry. Investigations were carried out utilizing advanced polymers due to their extraordinary physical and mechanical properties that could be an ideal substitute towards the reinforcement of concrete structures.

A case study presenting the practical applications and analysis for the use of advanced composite materials in the rehabilitation of deteriorated reinforced concrete structural members of an 8-storey building located in the city of Abu Dhabi were examined in this paper in comparison with the demolishing and reconstruction option of the building. The investigation undertook micro-concrete advanced composite materials as the main primary material to carryout the service life and life cycle cost analysis of the structural column elements to reach the most economical and effective solution to apply on the deteriorated structure. Although the research resulted in an extension of the service life of the structure by 9 to 12 years (± 1), the resulting repair cost for the deteriorated structural elements were determined to be higher initially by at least 11.1% with an overall lifecycle cost range between 24.7% and 32.3% higher than the re-construction cost of the said structure.

While there is a great potential in terms of environmental aspects, as well as the extension of service life possibility of the structure through the utilization of advanced composites in repairing and rehabilitation of concrete structures in the GCC region, it is presently determined not as feasible and cost effective preference.

Arabic Abstract

إن تدهور الخرسانة المسلحة في بناء الهياكل الانشائية يعود على عوامل عدة مثل الشيخوخة، وصدأ حديد التسليح، والرطوبة، والأكسدة، وأحداث التجميد والذوبان للماء الموجود داخل الخرسانة، والأحمال الدائمة المفروضة على الخرسانة المسلحة، بالإضافة للأخطاء المؤسفة نتيجة سهو في التصاميم الأولية التي يقوم بها المصممين قد حفزت الباحثون على البحث على مواد أكثر متانة ومستدامة للتمكن من استخدامها في إصلاح وتأهيل العناصر الهيكلية التي تدهورت.

أيضا، فإن ندرة المواد الخام لتصنيع الخرسانة، وزيادة أسعار مصاريف اللإنتاج، وضعف التحمل على المستوى الدائم والمخاوف من الأضرار البيئية الناتجة عن الإنتاج، وضرورة ايجاد مواد بديلة ذات وزن أقل مع الاحتفاظ بقوى عالية قد استلزم التوسع في الأبحاث لاكتشاف هذه المواد الجديدة ذات الخواص الهندسية العالية لتلبية الطلبات المتزايدة من البناء والتشييد. وعليه، فقد نتج عن هذه الأبحاث بأن استخدام البوليمرات المتقدمة لربما تحقق الغاية المنشودة وذلك بسبب الخصائص الفيزيائية والميكانيكية الممتازة و الغير عادية التي تكسبها القدرة على أن تكون بديلا مثاليا للديمومة لتسليح الخرسانة بدلا عن الحديد.

في هذه الدراسة، اعتمد الباحث على التطبيقات العملية والتحليلية لاستخدام مثل هذه المواد المركبة المتطورة في إعادة تأهيل الأجزاء الهيكلية المتضررة من الخرسانة المسلحة لمبنى مؤلف من ثمانية طوابق يقع في مدينة أبوظبي. بناءا عليه، اعتمد الباحث دراسة تكاليف المواد المركبة المتطورة الدقيقة المستخدمة في الخرسانة بالمقارنة مع المواد الأولية الرئيسية للوقوف على تحليل الكفائة في تمديد العمر الافتراضي للهياكل الخرسانية المتآكلة لتحديد الحل الأكثر اقتصادا وفعالية للتطبيق على مثل هذه المنشآت في الوقت الراهن. على الرغم من ان نتيجة البحث أظهرت تمديدا جيدا في العمر الإفتراضي للعناصر الخرسانية المتآكلة بحدود ٩ الى ١٢ عاما ()، فإن التكلفة الاجمالية المبدئية لا تقل عن ١١,١٪ زيادة عن كلفة اعادة البناء و التكلفة الإجمالية على عمر المنشأة الافتراضي قد تصل الى زيادة بمقدار ٢٤,٧٪ الى ٣٢,٣٪.

في حين ان هنالك إمكانات كبيرة عند استخدام هذه المواد البوليميرية المتقدمة من حيث اطالة العمر الافتراضي للمنشآت و حماية البيئة من المخلفات الناتجة عن اعادة الإعمار في دول مجلس التعاون الخليجي، إلا أن كلفة استخدام هذه المركبات غير مجدية اقتصاديا.

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Anas Dibsi

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Symbols

ACI	American Concrete Institute
ACMs	Advanced Composite Materials
ADCE	Abu Dhabi Commercial Engineering
AN	Acrylonitrile Fibers
BMP	Building Material Prices
C–S–H	Calcium–Silicate–Hydrate Reaction
C/Cl^-	Chloride Content
$Ca(OH)_2$	Calcium Hydroxide
$CaCO_3$	Calcium Carbonates
CaO	Calcium Oxide
CCI	Construction Cost Index
CCIA	Concrete Corrosion Inhibitors Association
C_{CO2}	Concentration of CO_2 at the Concrete Surface
CFRC	Carbon Fiber Reinforced Concrete
FRPC	Fiber Reinforced Plastics Composites
CFRP	Carbon Fiber/Fabric Reinforced Polymers
CI	Corrosion Inhibitors
CMC	Ceramic Matrix Composites
CNT	Carbon Nanotubes
CO_2	Carbon Dioxide
Conc.	Concentration
Cover (%)	The Clear Cover of Concrete Covariance Term
Cs (%)	The Maximum Surface Chloride Level in Percentage
Ct (%)	The Concentration of Chlorides Covariance Term on the Exterior Reinforcement Steel
CT/CAT	Computerized Axial Tomography
D(t)	Diffusion Coefficient at Time “t”
D28 (%)	The Initial Diffusivity of the Concrete Predicted at 28 Days
dC/dc	The Chloride Binding Capacity
D_{CO2}	Diffusion Coefficient for CO_2
D_{F1}	The Diffusion Coefficient in Fick’s 1st law
D_{F2}	The Diffusion Coefficient in Fick’s 2nd law
D_{ref}	Diffusion Coefficient at time t_{ref} and temperature T_{ref} (= 28 days in Life-365 program)
ECC	Engineered Cementitious Composites
ECPE	Extended Chain Polyethylene Fibers
FAA	Federal Aviation Administration
f_{cu}	Concrete Compressive Strength
FRC	Fiber-Reinforced Composites
FRP	Fiber-Reinforced Polymers/Plastics
$g.cm^{-3}$	Specific Gravity (Unit)
GCC	Gulf Cooperation Council
GFRC	Glass Fiber Reinforced Concrete
GPC	Golden Planners Engineering Consultants LLC
GRP	Glass Reinforced Plastics
CF	Carbon Fibers

HMPE	High Modulus Polyethylene Fibers
HMW	High Molecular Weight Polymers
HPF	High-Performance Fibers
IC	Initial Costs
IP/t_i	Initiation Period
LCA	Life-Cycle Assessment
LCC	Life-Cycle Cost
LCCA	Life Cycle Cost Assessment
m	Diffusion Decay Index (Constant)
m (%)	The Reduction in Diffusivity
Mesopitch-based CF	Petroleum-based Pitch Carbon Fibers
MMC	Metal Matrix Composites
MPa/GPa	Mega/Giga-Pascal Stregnth/Pressure (Unit)
PFR	Phenol Formaldehyde Resins
MRI	Magnetic Resonance Imaging
MWNT	Multi-Walled Nanotubes
NIST	Service Life Modeling Incorporated
NPV	Net Present Value
NRMCA	National Ready-Mixed Concrete Association
OPC	Ordinary Portland Cement
PAN-based CF	Poly-acrylonitrile based Carbon Fibers
PBO	Zylon, or Polybenzoxazole Fibers
PBT	Polybutylene Terepthalate, or Polybenzothiazole Fibers
PC	Polymer Concrete
PCC	Polymer Cement Concrete
PE	Polyethylene Fibers
PET	Polyester Fibers
pH	Scale of Acidity/Alkalinity
PIC	Polymer Impregnated Concrete
PMC	Polymer Matrix Composites/Polymer Modified Concrete
PP	Polypropylene Fibers
PP/t_p	The Propagation Period
PPCC	Polymer Portland-Cement Concrete
PRC	Particle(Particulate)-Reinforced Composites
psi or N/mm^2	Compressive Strength Unit (Pound per Square Inch or Newton per Millimeter Squared)
PVA	Polyvinyl Alcohol
HP-PE/HPPE	High Performance Polyethylene Fibers
R	Gas Constant
R.C./RC	Reinforced Concrete
R.C.C.	Reinforced Cement Concrete
Rayon-based CF	Cellulosic based Carbon Fibers
RH	Relative Humidity
ROI	Rate of Return on Investment
Struc.	Structure
SA	Sensitivity Analysis
SC	Structural Composites
SCAD	Statistics Center Abu Dhabi
SDC	Strategic Development Council
SLCA	Service-life Cycle Assessment

SMC	Soft Magnetic Composites
SR	Surface Resistivity
SRC	Sulphate Resisting Cement
SWNT	Single-Walled Nanotubes
T	Temperature
T	Absolute Temperature
T-1000 CF	A type of Carbon Fibers
t_r	The Period until the First Repair ($t_i + t_p$)
U	Activation Energy of the Diffusion Process (35000 J/mol)
UHMWPE	Ultra-High Molecular Weight Polyethylene
w/b	Water-to-Binder Ratio
WWII	World War II
x_{CO3}	Depth of Carbonation
x_d	The Amount of Chlorides that has to Infiltrate the Concrete Cover to Reach the Internal Reinforcement
Ω.cm	Electrical Resistivity (Unit)

Chapter 1

Introduction

1.1. Introduction

While concrete have been utilized as the primary building material for decades, the deterioration of reinforced concrete and the substantial damages to the civil infrastructure and buildings due to steel rusting and aging of the structures had imposed a great deal of research on various materials that can be utilized in the repair, rehabilitation, and retrofitting of deteriorated reinforced concrete structures.

Accordingly, the aim of this research is to evaluate and analyze the utilization of micro-concrete Advanced Composite Materials (referred to as ACMs) in terms of durability enhancement to newly planned structures and the possibility to prolong the service-life of deteriorated ones. In addition to extending the service-life possibility, the research compares the cost of prolonging the service-life of the structure in question against demolition and re-construction value utilizing the Life Cycle Cost Analysis (LCCA) technique. The undertaken case study comprises of a deteriorated eight-storey building in the city of Abu Dhabi.

The research is divided into seven chapters. The first chapter covers the introduction that portrays the field of study, the hypothesis, and summarizes the research study disputes. The second chapter covers the literature review, which discusses the development and previous works on ACMs as well as the service-life and life cycle cost analysis utilized in this study. The following chapter (chapter three) includes the service life and life cycle cost analyses that are used in analyzing the structure in the case study. Afterwards, the research methodology including the research approach, strategy, data collection, and applied software is portrayed in chapter four, while the results and discussions are followed in chapter five. Meanwhile, the researcher proposal is presented in chapter six, while chapter seven offers the conclusion and the researcher recommendations based on the attained results in chapter five.

The literature review focuses on the previous works and history made on Advanced Composite Materials (ACMs) throughout their first introduction within and after World War II (WWII) and their wide development in various aspects and arenas, especially in the field of structural engineering. In addition, it sheds the light on the deterioration of concrete in the gulf region and possible ACMs based solutions that could be proposed on newly planned projects, as well as rehabilitation of deteriorated reinforced concrete structures.

Similarly, chapter three offers different approaches to determine the service-life cycle assessment (SLCA) and life cycle cost (LCC) processes used on the deteriorated building in the case study. It defines the uncertainty constraints and probabilities in the data to be analyzed to predict the prolonged service life and cost implication of repaired concrete structures utilizing ACMs.

Accordingly, chapter three aims to offer a far-more reaching understanding on the service-life and life cycle cost methods and their respective economical affluence on the construction industry, including the interest, inflation, and discount rates. The latter involves a thorough analysis on the effects of various reliability and risk considerations affecting the overall extension of the service life cycle along with its respective cost implication.

While predicting a service life model of a deteriorated reinforced concrete structure utilizing basic factors that are constructed on “guessing estimates” such as the various economic and environmental conditions, as well as the concrete mixture type and inherent specifications are fairly adequate, uncertainties arise about some of these conditions. These uncertainties could vary the service life model by several years, such as the loading history on the structure, interest rates, temperature variations, and additives that are either added during casting of the concrete, or through the repair, rehabilitation and maintenance procedures that were previously done on the structural elements throughout the life-span of the built structure.

1.2. Research Significance

The accumulation of rust on steel reinforcement leads to the deterioration of essential reinforced concrete members, such as columns, beams, and slabs. As a result, the structure becomes more susceptible to chloride, chemical, and environmental attacks, which in terms affects the serviceability and life expectancy of the built structure. Accordingly, ecological, economical and sustainability concerns arose due to the increasing demand on scarce natural resources. Thus, the need of an alternative material is essential for researching a far-better and sustainable construction arose, which has the ability to withstand and rehabilitate such structures.

In addition, the significance of attaining a durable concrete relies in its ability to resist various weathering conditions, as well as the resistance to deterioration aspects caused by physical and chemical attacks. While recent demolished buildings in the Gulf Region had proven an endurance of around 35 to 45 years, the population growth and the expansion of buildings projects in the region necessitates a prolongation to the service life of the built structures to reduce the negative environmental and financial impacts on their respective countries arising from the continuous demolishing and reconstruction.

While most newly built structures are mainly designed based on the value of the concrete strength, the performance and durability of the structure is not receiving the same attention. The latter would lead into shorter service life and higher cost on the long term during their operational and maintenance period. An account for those shortcomings must be addressed properly during the planning stage of the structure's design. However, since most built structures did not consider the durability and performance of the structure as a key factor, the research focused on taking into account possible means of repair and rehabilitation measures to various structural elements. The latter measures are mainly to reduce the need of demolishing and reconstruction of new structures, which is not sustainable in terms of material consumption, environmental and cost efficiency.

The drawbacks are amplified in deteriorated structures, which are subjected to harsh environments such as humid areas, and structures built near seawater. The latter is especially significant in the United Arab Emirates as it lies in the Gulf region where the levels of humidity in the air is high, the elevated and fluctuated temperature values and fluctuations, as well as the presence of chlorides in the surrounding weather. The deteriorated structure case study is constructed and analyzed undertaking these conditions.

1.3. Research Challenges

While many service life prediction models were previously done in Japan, Europe, and North America, the lack of data for rehabilitation of built structures in the gulf region presents a major challenge in defining proper and suitable techniques of repair for deteriorated reinforced concrete structures. The reason behind this problem is mainly because the gulf cities are newly constructed. Forty years ago, there were neither proper infrastructure built nor high-rise skyscrapers in the gulf. However, the drastic shift in construction progress made during the past decades in the field within the region necessitates the study of repairing the built structures and possibly altering the design of newly planned developments to undertake into account the serviceability and durability of the built structures.

On the other hand, uncertainties form another problematic concern in terms of analyzing the service life of the structure. Generally, the service life of concrete is estimated based on its initiation period, which is defined as the duration commencing from the oxidization and rusting of the internal steel reinforcement till the time where the structure begins to fail. It is essential in this research to implement the uncertainty estimates in concrete service life by estimating the uncertainty limits on the initiation as well as the propagation periods.

1.4. Research Objectives

This study aims to attain the following goals:

1. Gain a better understanding of the service life of deteriorated structures in the gulf and possible methods of repair.
2. Prediction of the service life of a deteriorated structure especially in columns utilizing computer aided software (Life-365) in accordance with the American Concrete Institute (ACI) standards.
3. Attain the proper repair methods of the structure utilizing Advanced Composite Materials (ACM's), and specifically micro-concrete utilization in rehabilitation of deteriorated structures.

4. Perform the feasibility study on utilizing ACMs in repair against demolition and reconstruction of structures taking into account various economical, ecological, and environmental factors.
5. Perform a life cycle cost analysis on the structure to identify the probabilistic sense of utilizing various alternative repair methods in accordance to their longest service life probabilities.
6. Propose a cost efficient and sustainable solution for the case study.

1.5. Case Study

Assessing the validity of utilizing ACM's in repairing and rehabilitation of deteriorated structures in the gulf region in accordance with ACI standards necessitate performing a case study of an actual deteriorated building located in the region. Thus, the researcher took an existing building consisting of ground floor plus eight stories plus roof floors where a previous service life study was performed and compare it with the results performed by the researcher. In addition, the researcher intends to perform Life Cycle Cost Analysis utilizing the LCA technique on the deteriorated elements in the structure. The building considered in the case study is located in Tourist Club in Abu Dhabi, United Arab Emirates. The plan of the building is a rectangular shape with a central two cores, one for the lifts and the other for the staircase. The deterioration is mainly studied on sample from columns in various floors as well as a sample from the pile cap. The structural system of the building consists of hordy slabs (hollow-core slabs used to fill the thickness of the slabs) situated over beams and columns. The columns on the other hand are transferring the loads to the pile caps, which eventually transfer the loads to the piles.

Accordingly, the researcher will perform an analysis and modeling comparison on a submitted structural integrity testing report by eFORCE Consultancies for repairing of a deteriorated concrete building in the city of Abu Dhabi in the United Arab Emirates for Plot No. C-74 located in East 13 of the city.

In the following literature review, the researcher will review various composite materials that acquire a possible potential in terms of the imposed impact loads, damages and deformation sustained by various composites, as well as various repairing and rehabilitation techniques of deteriorated structures. Meanwhile, the researcher will introduce the service life model method used in analysing the case study along with a brief about the life cycle cost analysis of the said structure.

Chapter 2

Literature Review (LR)

2.1. Overview

Concrete is a reliable building material that had been used for eras. It had been utilized in various kinds of structures ranging from infrastructure applications to buildings. It is considered to be one of the oldest materials in which substantial progress in the past couple of decades had been made to improve its strength and performance. However, the progress made in the development of concrete in construction field is less than those made in other industries due to the lack of sufficient data from performed research. Nonetheless, significant milestones were achieved in the advancement of the building material due to the vast population growth, as well as the increasing demand on housing, commercial, business units and various infrastructure structures.

During the past couple of decades, concrete acquiring substantial compressive strength was utilized in various construction projects. While high performing concrete products exhibited great stiffness and rigidity towards compressive stresses, the resulting built structures lacked the essential ductility and tolerance towards tensile stresses. Thus, steel sustained its importance as the primary reinforcement that is able to resist elastic tensile forces in concrete. In fact, the brittleness of concrete increases along with the compressive strength as the concrete retains a low ductility property. The latter characteristic postures a probable risk and constraint on utilization of superior strength concretes in construction applications. Under severe loading, specific areas where concrete and steel are bonded together could get fractured in the concrete matrix due to the high tensile stresses imposed. As a result, the structural elements disintegrate and eventually may lead to a devastating failure.

Therefore, the need of a more ductile and durable concrete became a necessity, especially considering seismic response applications. Accordingly, an elastic concrete could significantly improve the structural earthquake resistance (Li, 2013) [1]. Many researches were carried out and newly developed methods and procedures resulted in the discovery of various composite materials, especially those of fiber-reinforced composites nature, that may substitute steel reinforcement and lessen the impact of deterioration, as well as the financial expenses imposed by the employment of such type of reinforcement in concrete structures. The progress made in various composite materials could permit a prolongation in the structures service life whether it is planned or already built. Also, it may prevent or reduce a great deal of operational and restoration/repair costs. Whereas repair, restoration, and rehabilitation of deteriorated concrete is becoming a necessity due to the deprivation of the concrete matrix that are caused by the imposed stresses resulting from rusting of the reinforcing steel (Blanksvärd et al., 2009) [2].

As stated earlier, the deterioration of reinforced concrete and the substantial damages to the civil infrastructure resulting from rusting of steel (Figure 2.1 below), as well as the aging of the structures had imposed a great deal of research on the material to be utilized in the rehabilitation and retrofitting of the concrete structures. Furthermore, the reformation, renovations, and function alterations applied on the structure after construction, as well as various sustainability factors affecting the built structure and inaccuracies/errors made during the design and/or construction stages have contributed to the advancement of composite materials.

Figure 2.1 - Corrosion of Steel Rebar in Concrete

Source: Lewis, O. (2016) [F1]

The development of composites initially began in the field of aerospace gears to withstand different types of mechanical stresses, as well as reduce manufacturing costs. Recently, interest in composite materials gradually increased for the rehabilitation of structures in civil engineering field. It had become exceptionally appealing to use in civil projects throughout the planning stage towards the construction phase as a substitute material to steel that would allow the designed structure to withstand high tensional imposed forces, yet endure various environmental conditions. The choice of composites was primarily due to their excellent characteristics and remarkable strength, as well as stiffness/density proportions, composites were utilized in infrastructure projects, as well as diverse civil engineering applications (Pattanaik, 2009) [3].

Many composite materials are widely accepted as a durable material which acquires extraordinary physical properties such as their high-strength to weight ratios, corrosion and climate resistant, chemical resistant, lightweight, economical, and can be formed into any profile and extent to support the structure, such as FRPs and Particulate Concrete Composites (Bai, 2013; Custódio et al., 2009; Guedes et al., 2000) [4,5,6].

While a great deal of studies had been conducted on the durability of concrete utilizing advanced composites, very little data are available concerning the outcomes of concrete repair/rehabilitation using these composites towards the deteriorated components of the concrete structure. Nonetheless, the progression made in the past couple of decades in ACMs made it possible to rehabilitate the deteriorated structures utilizing Micro- and Nano- concrete technologies (Rana et. al, 2009)[7]. These technologies unlocked tremendous possibilities in the field of repairing and rehabilitating deteriorated concrete structures.

2.2. Deterioration of Reinforced Concrete in the GCC Region

Upon the discovery of oil and the vast economical gained in the Arabian Gulf during the past century, the region has experienced substantial growth in the construction field. Accordingly, the region experienced an extensive expansion in developments covering a wide range of arenas, such as infrastructure, commercial, residential, and industrial sectors. Conversely, since many of these old structures are reaching the end of their service life, the need of a more durable concrete as well as introduction of new building materials that serves the rehabilitation and restoration of deteriorated structures arise. While demolition and reconstruction is currently the main option, it is neither considered ecological nor economical considering the cumulative amount of deteriorated structures and the extent of pressure on the utilization of scarce natural resources.

Meanwhile, the environmental conditions of the region are considered one of the most aggressive in terms of exposure to various weathering and surrounding influences. According to Al-Samarai (2015) [8], the region climate varies from one area to the other that ranges in ‘Hot-Dry’ and ‘Hot-Humid’ climatic zones, whereas the temperature can reach up to 50 °C and can vary by 30 °C, while relative humidity levels ranges between 40 to 95% throughout summer. Consequently, the severe exposure conditions results in speeding up the oxidation process in steel reinforcement that in turn results in rusting of the reinforcement. As a result, the concrete properties get distorted through the alteration of applied thermal and mechanical stresses.

A specific technique that could reduce the amount of scarce natural resources used, as well as the rubbles waste and consumed valuable landfills from demolition was identified by Sami W. Tabsh and Akmal Abdelfattah (2009) [9]. The method utilizes the recycled concrete wastes from demolished structures in order to use them in new concrete batches. The study suggests that the produced concrete is lower than the conventional one, which utilizes natural aggregates, by 10% - 25% (Tabsh and Abdelfattah, 2009) [9]. However, since the study emphasizes on recycling more than durability and prolongation of the service life of existing structures, the method is regarded inadequate to the researcher’s study.

Another particular system that utilizes composite materials is currently widely used in newly developed projects, as well as repairing deteriorated reinforced cement concrete structures (R.C.C. structures) materials for deteriorated structures are referred to as polymer-modified fiber called fiber-reinforced polymers/plastics (FRPs) or dry fibers (Pattanaik, 2009) [3]. They are made of either carbon or glass fibers that have the ability to be fixed and attached to the concrete exterior surface to enhance and strengthen various structural members. In addition, FRPs can be designed to substitute steel reinforcement rebars through substitution of the concrete reinforcement with glass fiber-reinforced polymer rebars, or fiber reinforced polymers/plastics (FRPs) around columns to support torsional and momenta forces.

While FRPs materials are famous for their outstanding properties, they had been utilized mainly in aerospace and mechanical engineers. Only until recently through the past couple of decades did the FRPs attain the required attention in the civil construction field.

Since the primary purpose of attaining high-performance materials is to substitute heavy/dense metals that de-bonds and deteriorate concrete when corroded, FRPs and various other advanced composite materials proved to be a promising solution in the civil structural field whereas it permits the structure to resist greater stresses while reduce the long-term maintenance and repairing costs. In addition, FRPs possess low molecular weight, and therefore, are considered more efficient to be utilized in concrete structures due to their outstanding physical and mechanical properties, and higher efficiency in terms of raw material consumption (Hollaway, 2010; Zaman et al., 2013) [10,11].

Many researches were performed on composite materials that resulted in a global acceptance as a durable material which acquires extraordinary physical properties such as their high-strength to weight ratios, corrosion and climate resistant, chemical resistant, lightweight, economical, and can be formed to any profile and extent to support the structure, such as FRPs and Particulate Concrete Composites (Bai, 2013) [4].

Beside FRPs, other developed ACM materials emerged as researches progressed, such as carbon fabrics (CFRPs), polymer, ceramic, metal matrix composites (PMCs, CMCs, and MMC's respectively), micro-concrete particulate composites, and Engineered Cementitious Composites (ECC). Many of them were proven efficient in retrofitting and rehabilitation of damaged and deteriorated concrete structures, such as CFRP's, PMC's, micro-concrete particulate composites, and ECC. Meanwhile, PMCs, CMCs, MMC's, as well as ECCs were utilized directly within new developments. The essentiality of utilizing composites relies on the application and service criteria of the designed/rehabilitated structure (United States Congress, 1988) [12].

These newly developed composite materials offered a beacon of hope to a more advanced material that is ought to be used in order to prolong the durability of the designed structures, as well as repair, rehabilitate, and extend the service life of deteriorated ones in the gulf region.

2.3. Environmental considerations

Among the most significant obstacles in today's culture is the concern of waste recycling. Nowadays, more than four billion tons of municipal solid waste is produced each year globally. Plastics, paper, construction material and other various organic waste alone amounts of up to 27% of the total municipal waste (Yeheyis et. al, 2012) [13].

During the previous era, numerous techniques were developed that could possibly be utilized to reuse or reuse waste polymers; however, only a limited number of methods were realized to be the solution to overcome this challenge. One appealing approach is referred to as mechanical recycling. This method utilizes the waste polymers to be recycled and reused by reformulating it to be plastic. Accordingly, further investigations were carried in terms of reusing thermosets in numerous applications such as plastic beams, door sections, as well as infrastructure construction materials (Bai, 2013; Conroy et al, 2006) [4,14].

Similarly, recycling polymer composites as polyester-based structural materials have revealed a great deal of success in the production solar and energy wind equipment. Thus, the recycle and reuse process of the polymer composites outcome could change the trends of future alternative energy owing to the limited fossil fuels resources (Bai, 2013; Ratna and Mohana, 2011; Sathishkumar et. al, 2012) [4,15,16].

The contents of this paper are more extensive through the delivery of significant recommendations to plan an in-depth investigation focused on the area of research to adequately address the practical techniques of rehabilitating structures. While the latter can be performed through various techniques, such as Polymer crack-injection, substitution of structural element cover with PMCs, CMCs, MMCs, Micro-concrete

Fiber-Reinforced Polymers as well as the implementation of FRPs and CFRPs substrate to accommodate for the loss of tensional resistance ability of the deteriorated reinforced concrete elements, the assessment in this study will focus on utilization of micro-concrete particulate composites that are readily available in the market under different brands.

2.4. Plastics and the Construction Industry

The utilization of plastics in the construction industry was initiated in the late 1960's. However, the lack of adequate research and data available in terms of polymers at that period of time led to intrinsic chemical, physical, and mechanical inconsistency. Consequently, issues related to the function and durability of the produced material was evident. While polymers were broadly employed in repair of deteriorated concrete elements through various applications, it was not properly understood till the late eighties of the past century (Gemert, 2003) [17].

Consequently, the concept idea for the development of enhanced plastics was originated. The recommendation was directed towards reinforcing plastics with a readily available material in the market such as glass fibers. The latter would boost the pressure and stresses resistance during the making process. The created molds satisfied the intended objectives and presented a sufficient satisfactory degree towards the resistance of stresses. They were fabricated using phenolic resins in combination with glass fibers. Beside constructions, phenolic resins were integrated along with organic reinforcements namely timber flour filler to be utilizes in various products such as, but not limited to: telephones, televisions, radios, and many other products (Bai, 2013; Lewark, 2007; Frollini and Castellan, 2012; Brent 2002) [4,18,19,20].

The reinforcing fibers in a matrix are responsible for boosting the engineering properties of the fabricated product, while the matrix assist in protecting and stabilizing of the fibers. Concrete, for example, is a form of combination of multi-types of aggregates and cement. The result of combination of two or more materials performed through a sufficient and adequate design is a new material attaining the properties of its constituents. In addition, they come in a variety of forms, some are natural, such as wood, which is a blend of cellulose fibers and lignin matrix, and bone structure, while others are synthetic like tires, fiberglass, and fiber-reinforced polymers that are composed of steel or polymer fibers and rubber matrix, chopped fibers and polyester, and fibers embedded into plastics respectively. Natural fibers are considered a better choice in terms of sustainability for engineers, as they are denser, yet lighter in weight and has lower environmental impact in terms of production and recovered energy and carbon at the end of the fiber's service life (Joshi et al., 2003) [23].

In general, composites are a combination of several components that yields a novel material with superior properties. Basically, composites comprise of a matrix resin/medium plus additives. These additives can either be particle-reinforced, fiber-reinforced, or structural laminates. The particulate-reinforced composites can be extremely small (less than 25 microns), while the fiber-reinforced composites can either be particulate (chopped fibers, or short fibers) or normally fiber-reinforced composite (continuous fibers) (Altairenlighten.com, 2016) [22] as illustrated in Figure 2.2 below:

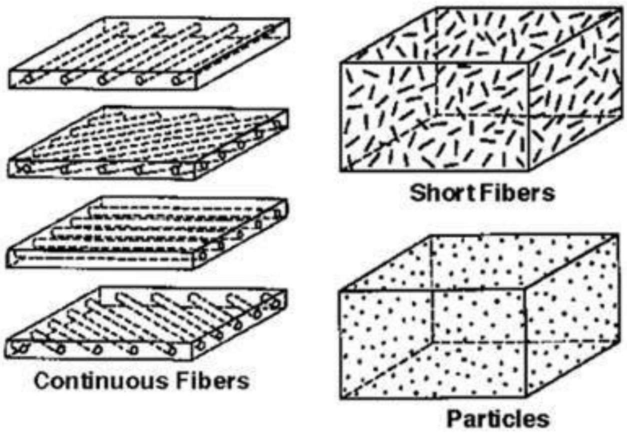


Figure 2.2- Types of Fiber Reinforcements in Composite Materials

Source: Fooyah Entertainment Network (2016) [F2]

The prime interest in structural engineering composites relies upon the composites ability to reach an efficient and desirable strength while maintaining its weight reduction and increasing its ability to resist corrosion. In order for the composite to transmit the imposed stress efficiently, composites shall be designed as assemblies of layers referred to them as laminates. These composite laminates deliver the requisite engineering properties necessitated by the application and form required as will be demonstrated in 2.5.1.

2.5. Composite Materials

In general, composite materials consist of a combination of two materials in which each material acquires significantly distinctive physical or chemical properties. The resultant is a product that attains new properties than each of the individual material. Composites had been reportedly used in construction as early as the fifteenth century using mud bricks strengthened with stacks of hay (Figure 2.3 below). Then again, the origination pertaining to the present time for composites could be associated with the fact that glass fibers were made available in the market during World War I. Back then, the airlines sector faced a production challenge: unique materials became necessitated to acquire the sophisticated concept designs that were developed (Bai, 2013) [4].

Figure 2.3 - Mud-bricks Reinforced with Straw/Hay

Source: Potter, K. (1996) and Groh, R. (2016) [F3]

The development of composites was rapider during World War II especially in the military aircraft field. Phenolic resins were combined with different reinforcement such as paper, unbleached flax yarn, and different types of fibers to produce the Fairchild PT-19 aircraft, as well as the fuselages respectively (Bai, 2013; Brent, 2002; Suddell and Evans, 2005) [4,20,21]. Additionally, phenolic-cotton and phenolic-asbestos were introduced to produce ship bearings, switchgears, and brake linings (Bai, 2013; Brent, 2002) [4,20]. However, after World War II, a decreased interest was observed in the development of advanced composites due to the availability of economical oil and petrochemicals. Nonetheless, the interest grew back in the past couple of decades due to ecological reasons.

Composites are classified into Particle (Particulate)-Reinforced Composites (PRCs), Fiber-Reinforced Composites (FRCs), and Structural Composites (SCs). The PRCs can compose of either large or dispersion-strengthened particles and is idealistically utilized in strengthening concrete structures. The dispersion-strengthened particles are most commonly used in micro-concrete applications, such as rehabilitation and retrofitting of the structure. On the other hand, the FRCs are classified into either continuous or discontinous fibers, while the SC consists of either laminates or sandwich panels.

2.5.1. Laminates and Hybrid Laminates of Composites

In general, laminates are normally applied to cover various directional stresses in the matrix resin. While uni-directional laminates fails at higher applied forces than cross-ply laminates, it tends to sustain its strength mainly through the applied orientation. Accordingly, if the composites in question comprise of fibers, they become reliant on their direction as illustrated in Figure 2.4 below, they tend to acquire altered properties if alignment is adjusted based on their anisotropic nature. Therefore, composites that utilize fiber are more process oriented and delicate than isotropic materials. Meanwhile, the cross-ply laminates can resist various stresses from different directions and are more recognized in areas where compressive strength is necessitated (Kominar et al., 1995; Roylance, 2000) [24,25].

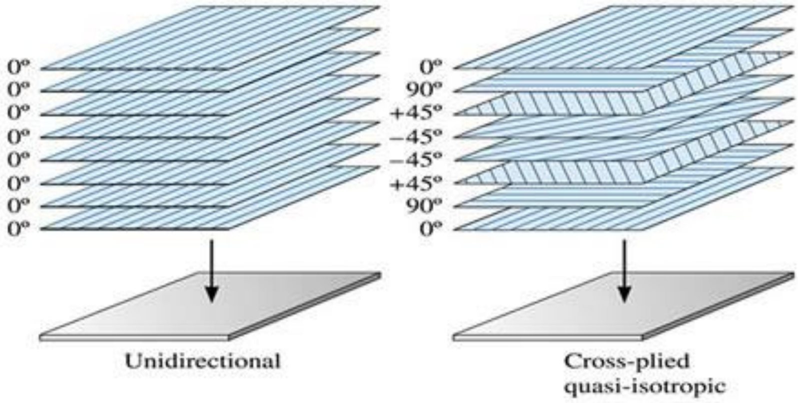


Figure 2.4 - Lamination Stacking on Composites.

Source: Quartus Engineering Inc. (2016) [F4]

Wood or concrete covered with polymers or FRPs are recognized examples of advanced composite materials. Advanced hybrid composite laminates, on the other hand, are a form of hybrid composite material that is laminated and can be utilized in structural engineering, such as Carbon Nanotubes (CNTs), to create an even better advanced composite as necessitated by the designer desired criteria and application (Garcia et al., 2008) [26]. The best results are attained when a laminate is designed and procured in a uni-directional orientation with the direction of stresses as illustrated in Figure 2.4 above.

2.5.2. Advantages of Composites

Composite materials present excellent physical and mechanical characteristics. These characteristics are illustrated as follows:

2.5.2.1. High strength and stiffness to weight ratios

According to Robert M. Jones (1998, p.27) [27], composite weight is usually small due to the low-density characteristic of embedded fibers within the matrix. In addition, they exhibit outstanding strength that is way sturdier than metallic materials, such as aluminum or steel, while maintaining lower weights compared to commonly used materials. Accordingly, the stress amount that can be subjected to a composite prior to failure is much higher than the typical steel reinforcement utilized in the construction industry (as illustrated in Figure 2.5 below). As a result, numerous industries rely on composites in manufacturing their components, such as aircrafts, transportation vehicles, infrastructure, and construction industries. Thus, these industries necessitate the utilization of composites to decrease weight and thereby reduce the amount of consumed fuel to reach the required speed in lower time duration and attain better efficiency. On the other, utilizing composites in infrastructures (such as bridges, and buildings) decrease the overall weight of the structure by using less cement. The key result is to attain superior structural properties with less material while bearing in mind the ecological factors in preserving the environment.

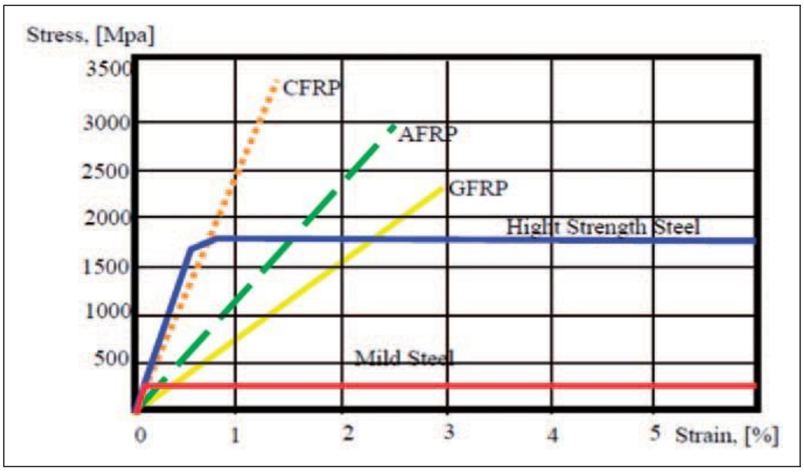


Figure 2.5 - Stress-Strain Curves of Some FRP Composites Compared to Steel

Source: Zaman et al. (2013) [11] & [F5]

2.5.2.2. Chemical and Corrosion Resistance

Oxidation commonly occurs in structures built with steel. However, composites, such as FRPs, resist corrosion attacks as the oxidation process is eliminated due to the non-conductivity characteristics of the embedded fibers. Moreover, structures build with composite materials can survive severe environmental and chemical attacks due to the non-reactivity properties of the composite. Furthermore, specifically designed enhanced composites such as advanced composite materials (later defined and referred to as ACMs) are able to resist broad range of temperature and thermal variance (Singha and Thakur, 2009; Mallick, 2007) [28,29].

2.5.2.3. Impact Resistance

Sudden forces are one of the most critical issues faced by various industries. However, a properly designed composite can sustain impacts loads much greater than the common used materials. This is particularly important in applications where impact loads/forces/stresses are occurring frequently, such as but not limited to blast proof oilfields buildings, armored vehicles, bullet proof articles, and nuclear plants (Cantwell and Morton, 1991) [30].

2.5.2.4. Design Flexibility and Custom Tailoring of Composites

Specifically designed applications require particular shapes and sizes/dimensions in relation to the applied stresses. While many typically used materials, such as metals, can be custom tailored; processes involved in tailoring such materials are deemed expensive, difficult, and unsustainable. Unlike other materials, composites can easily be molded into various forms according to the desired application and thereby giving the designers more flexibility in their designs. Due to the freedom of composite designs and ease of molding into various shapes, numerous applications are utilizing composites in their structural design. The latter allow composites to be specifically designed to achieve a high stiffness in a preferred direction with negligible increment in weight (Mallick, 2007) [29]. Meanwhile, composites finishing textures can be altered from smooth to lumpy to suit the finishing necessities of the designed structure and can be casted on site (Composites Lab, 2017) [31].

2.5.2.5. Total Material Cost and Composite Consolidation

As stated earlier, utilizing of composites lowers the weight and amount of materials used to produce the desired product. While composites fabrication cost is higher than the usual materials, the overall cost of the desired structure can be lower than the original building cost. Thus, composite materials can substitute various excessively used building components, such as metals, while maintaining the required engineering properties and integrity of the structure. As a result, the cost and time of manufacturing of the desired material decrease and the service life of the structure is increased. Consequently, aircraft, automobile, and construction industries profoundly rely on composites (Jones, 1998, p.27) [27].

2.5.2.6. Structural Dimensional and Volumetric Stability

While commonly utilized materials, such as wood or steel, change its dimensional physical properties when subjected to liquids or various temperatures, composite materials preserve their physiognomies in terms of form and volumetric dimensions when exposed to these conditions. Wood, for example, increase and decrease in volume accordingly to humidity level in the surrounding environment. Thus, composites present a superior performance in challenging circumstances that are required in confined arrangements that necessitate dimensional stability such as space telescopes, aircraft wings, and concrete arc shells (Yoon et al., 2014; Veenendaal and Block, 2014) [32,33].

2.5.2.7. Non-conductivity of Composites

Unlike metals, composites do not conduct electrical current. Consequently, reactions that occur in metals, such as oxidation process in steel rebar, or transition of electricity in electronic circuits and poles are eradicated. However, electrical conductivity property can be added to the composite if required through the utilization of specific constituents design. If properly designed, the latter yields a lightweight, an electrical resisting, and a low thermal conductive material that can be utilized in specific construction projects (Khedari et al., 2001; Rapid Composites LLC, 2016) [34,35].

2.5.2.8. Nonmagnetic Features of Composites

Since composite are not comprised of metals and their electrons spins are balanced, they do not possess magnetic capabilities. Therefore, they are utilized in numerous telecommunication, electronics, and sensitive medical electric applications, especially in the construction of hospitals and manufacturing of imaging equipment, where the imaging equipment's magnetic field is high, such as CT-scan (known as CAT Scan or Computerized Axial Tomography), and magnetic resonance imaging (known as MRI). In addition, they nonmagnetic composites can be utilized in naval vessels to reduce/eliminate radar detection (Mouritz et al., 2001; Werne, 1998) [36,37]. On the contrary, micro-composites could possess trivial magnetic features if Soft Magnetic Composites (SMC's), such as steel powder, is utilized instead of chopped fibers (Hultman and Jack, 2003) [38]. Thus, the application of the composite plays a major role in identifying the composite constituents.

2.5.2.9. Radar and Sonar Stealth Characteristics of Composites

Radars and Sonars had been used in plenty of applications and sectors ranging from military aircrafts and vessels to infrastructure transportation monitoring. The signals emitted by the radar (above water) or sonar (under water) does not echo back to its origin. Thus, it makes it an ideal choice as an advanced technology to be utilized in military and aerospace applications. Nowadays, stealth fighter jets and naval vessels that are almost undetectable are being manufactured using these advanced composites especially in the United States and other great powers (Mouritz et al., 2001) [36].

2.5.2.10. Low Thermal Conductivity

Thermal conductivity is considered a key component in designing structures. Composites acquire an extremely low thermal conductivity levels that permits its usage extensively in innovative fields such as aerospace, aeronautics, electrical and electronics, mechanical, plumbing, and civil structural engineering. Enhancing the thermal conductivity level in the desired product will result in gaining better performance and less deterioration rate (Khedari et al., 2001) [34].

2.5.2.11. Composites Insulation Capability

Since composites are non-conductive in terms of electricity and acquire a very low thermal conductivity levels, they serve as a protective shield against electricity, heat, and cold weather. Thus, they acquire insulation capabilities that can be utilized in applications related to electric poles, circuit manufacturing, and can be used in general insulation products. Other than composites electrical applications, composites presently are utilized in various construction fields as an excellent thermal insulator. Applications in architectural and civil engineering are typically seen through the utilization of composites in doors, panels, windows, and rubber as insulators to protect against water leakage, as well as diverse harsh climate conditions (Rapid Composites LLC, 2016) [35].

2.5.2.12. High-energy absorption properties acoustic and seismic responses

Composites acquire extraordinary capabilities in terms of energy absorption. Utilizing high-performance fibers with high strength and ductility properties such as Nylon, polyethylene (PE), and polyester fibers (PET) gives the composite the ability to dissipate the energy through flexural plastic deformation of the composite (Morye et al., 2000) [39]. Since composites can be fabricated to attain high stiffness structures, they can be utilized in structures where seismic resistance is vital. Likewise, composites are able to absorb high-energy acoustic waves through the woven fabric structure of the material and their very low Poisson's ratio (Zhu et al., 2015) [40].

Seismic applications of advanced composites in civil structural engineering are usually associated with increasing stiffness or the addition of composite seismic dampers/isolators. The latter absorb and dissipate the energy forces through various techniques. The resulting structure tends to resist earthquakes as illustrated in the base isolation damping system presented in Figure 2.5 below:

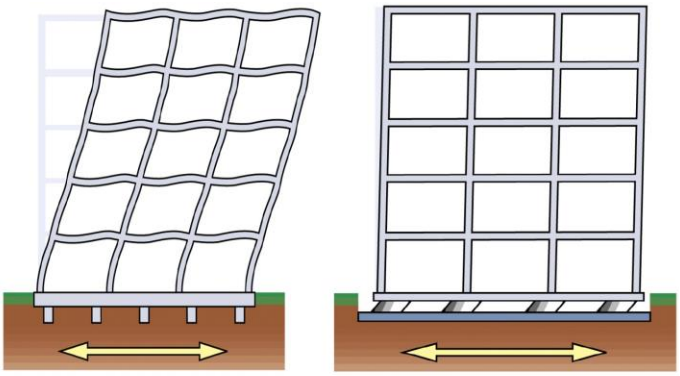


Figure 2.6 - Behavior of Building Structure w/o (Left) & with (Right) Base Isolation System

Source: Sharma, M. C. (2016) [F6]

2.5.2.13. Durability of Composites

Unlike steel, composites do not react water, fluids, and other chemicals and acquire an excellent resistance capability to such matters. As a result, de-bonding between the composite and matrix is very unlikely to occur. In reinforced concrete (RC), employment of composites as a reinforcing agent could eliminate the root cause of the deterioration of concrete and therefore extend the service life of the structure significantly. Hence, products that utilize composites in their structure tend to last much longer than commonly used materials with the least maintenance cost. Some researchers claim that composites can last up-to a century, while others debate that it could only survive half of that limit (Karbhari, 2007) [41].

2.5.2.14. High Fatigue Life of Composites

Fatigue of composites is a major concern that had its share in by researchers. The main apprehension of this problematic subject is due to the anisotropic physiognomies possessed by composites and the striving efforts of determining the various failure mechanisms of composites subjected to static and cyclic loadings. This phenomenon is considered critical that governs the strength of a composite (Hashin, 1981) [42].

Unlike metals, which are of an isotropic nature, composites embedded with fibers, such as fiber-reinforced plastics (FRPs) do not present a single crack failure mechanism, rather, they demonstrate a non-linear behavior that are inherent from the composites anisotropic properties. While metals possess strengths in various directions, FRP composites resistance ability is limited to the direction of applied stresses. Consideration must be taken in terms of the exhibited cracking behavior of the matrix, surface delamination, and fiber rupture/pullout from the matrix, as well as the longevity endurance bonding ability of the designed composite (Jollivet et al., 2013) [43].

Nonetheless, various composites were previously investigated through plenty of studies that revealed that such composites acquire a high fatigue resistance capability in various applications. Hence, composites can prolong the service-life and durability of the structure.

2.5.3. Encountered challenges in utilization of composites

2.5.3.1. Cost of raw materials and fabrication

Procurement of the composite material and fabrication process can be quite expensive due to the high cost of its raw materials. In addition, the production, fabrication control and testing measures in the production of an efficient composite material can be challenging due to the complexity processes in attaining the desired composites. Currently, the availability of composites comprised of matrix and fiber is increasing and the cost of composites is getting reduced. The latter is mainly due to the growth in production and the ongoing development and recent advancement of factories and methodologies in assembling the necessitated composites as more industrialists are seeking to produce various kinds of carbon fibers. Hence, carbon composites are getting more competitive and cost effective (Rao N. et al., 2015) [44].

2.5.3.2. Possible weakness of transverse properties

As stated earlier, in a particular direction, composite laminates exhibit stronger ability to resist loads imposed if the laminates are unidirectional aligned along with the direction of the imposed stresses. On the contrary, composite laminates are less strong if the imposed stresses are in transverse direction with the laminates. However, this problem can be surpassed if multi-layers of laminates are produced with fibers in implemented in various directions (Campbell, 2010) [45].

2.5.3.3. Weak and low stiffness matrix

The matrix medium assists in protecting and stabilizing of the fibers. However, some polymers may have a low strength and stiffness, therefore, if the matrix is weak, the fibers may not be able to sustain its desired engineering properties and therefore the composite is deemed deficient. Thus, the phenolic resins of the matrix must be chosen carefully to overcome this challenge (Campbell, 2010) [45].

2.5.3.4. Environmental degradation of matrix

The surrounding matrix shall be able to withstand various environmental conditions. As stated earlier, if the matrix becomes weaker due to high matrix degradation rate, the composite fibers may not sustain its designed criteria. Thus, the overall serviceability of the composite render useless (Campbell, 2010) [45].

2.5.3.5. Additives Bond in Composites

Additives bonding with the surrounding matrix could be challenging especially in applications related to metals. Metals expand and contract based on the surrounding temperature, while composites are less affected by temperature. Thus, de-bonding of metals and composites are weak and may achieve its desired application. Similarly, concrete bonding with metals is far superior to that of composites. However, this obstacle can be surpassed through altering the constituents and design of the composite matrix to attain the desired material. In addition, this challenge can be overcome by using advanced bonding techniques in the composites such as electro-beam processing as described by Goodman and Palmese (A.K. Kulshreshtha, C. Vasile, 2002) [46]. On the other hand, cementitious composites, such as micro-concrete composite, can overcome this challenge as the concrete forms a robust bond with micro-fibers in the matrix.

2.5.3.6. Analysis Complexity of Composites

According to Z. Hashin (1983) [47], various properties of different composites were analysed taking into consideration: elasticity, thermal expansion, moisture swelling, viscoelasticity, conductivity, static strength, and fatigue failure, whereas the analysis of composites is deemed complex and challenging due to the numerous factors affecting the composite structure. Starting with production, the choice of fiber/additive and the applicator competency to perform the addition of the composite and analysis of defects/flaws within the obtained matrix can be problematic. Microscopic deficiencies found in the composites due to incorrect design of constituents or the competency of the applicator could adversely affect the overall performance of the composite. Testing and analysis of the previous subject is challenging and time consuming (Mallick, 2007) [29].

2.6. Advanced Composite Materials

Advanced Composite Materials (ACMs) are composites produced thru the utilization of a fibrous material (either strands or particulate) that are implanted within a resin matrix. They are typically laminated with fibers aligned in interchanging directions to provide the final product with the necessitated strength and stiffness (Federal Aviation Administration, 2012) [48]. In order to enable a consistent and uniform load distribution, the bonding between the matrix resin and the strengthening agent is essential (Bai, 2013; Pilato and Michno, 1994) [4,49].

Advanced composite materials (ACMs) are commonly recognized for their ultra high strength, stiffness, and modulus of elasticity fibers that are able to bond with weak surrounding media and extend the service life of structures, especially when utilized in the repair/retrofit/rehabilitate of deteriorated reinforced concrete. While there are many reinforcing fibers that are readily available in the market, only the fibers that acquire extraordinary strength and modulus with relatively low weight, as well as good resistance towards heat and environmental surroundings can serve as a satisfactory structural material and are considered high-performance fibers that can be utilized in ACMs (Jones, 1998) [27].

Furthermore, advanced composites are able to substitute steel in numerous applications and fields such as the utilization of carbon nanotubes (CNTs, Figure 2.4 below) in various structures structural elements including, but not limited to: the utilization of CNTs as concrete reinforcement in civil structural engineering, cargo liners and aircraft industry in aerospace engineering applications, auto-parts in mechanical engineering applications that requisite resistance to elevated stresses, as well as various medical applications. (Pilato and Michno, 1994) [49].

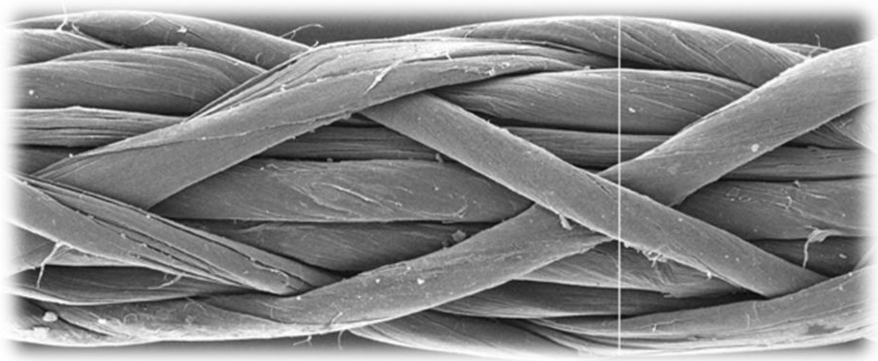


Figure 2.7 - Carbon Nanotubes

Source: Nanocomp Technologies in Cass, S. (2009) [F7]

Accordingly, ACMs presented far more reaching and established recognition in terms of functions in the field of structural engineering. This can be apparent in the continuous research and development that is being performed in the aerospace, civil, and medical engineering. Moreover, ACMs are extremely appealing for structural engineering due to their durability and stiffness properties. Nowadays, ACMs are being used in plenty of civil structural fields such as the design of a durable transportation infrastructure and building structures, as well as the repair/retrofitting of existing deteriorated concrete structures.

On the other hand, enhancing systems utilizing epoxy advanced composites, such as boron-epoxy composites as the connecting mediator and stabilizer, presented a great deal of success in regards to bonding with concrete and the desired function. On the contrary, disadvantages are found due to the lack of guidelines and methodology availability to deal with the epoxy composites, which could impact our health negatively in terms of skin allergies/diseases (such as acute and chronic dermatitis), whereas 80% of patients found are directly linked to the poisonous constituents of the epoxy resins used. (Calnan, 1975) [50].

Construction applications utilizing epoxy resins presented poor porosity and dispersion concentration, which may aggravate the freeze and thaw effects, as well as the steel oxidation process on the applied surfaces. Furthermore, epoxy advanced composites have low thermal compatibility with the concrete matrix that could trigger damaging effects on the matrix (Green et al., 2000) [51].

2.6.1. Thermosets vs. Thermoplastics of ACMs

The structural assimilation of an advanced composite material can be either a thermoset or thermoplastic. The commonly used thermosets and thermoplastics come in the form of plastics, which are made from polymers that define their characteristics, and are used in ACMs to fortify the composite. The primary difference between thermosets and thermoplastics is that the latter can be liquefied and recycled, while the thermoset plastics cannot be altered or recycled after the end-use product is formed. Although thermoplastics are more sustainable, the most commonly utilized plastics in ACMs are the thermosets due to their economical advantage and heat resistance ability (Modor Plastics, 2017) [52].

2.6.1.1. Advantages and Disadvantages of Thermosets

According to Modor Plastics (2017) [52], the advantages of thermoset plastics lie in its ability to resist elevated temperatures and maintenance of its strength, flexibility in molding to various shapes and sizes, resistance to chemical attacks, superior structural and dimensional integrity, and maintaining lower costs than thermoplastic polymers. However, ecological concerns arise from the use of thermosetting resins due to their incapability to be recycled or altered in shape and size, as well as harder to surface finishing the final product.

2.6.1.2. Advantages and Disadvantages of Thermoplastics

On the other hand, thermoplastics acquire superior abilities than thermosets, such as higher strength, higher strain and shrink resistance, higher chemical resistance, as well as ease of remolding and recycling. Due to their high strength and superior strain, thermoplastics are able to undertake elevated impact loadings applied on the structure. Since thermoplastics can be remolded, reshaped, and recycled, they are considered more sustainable and ecological than thermosets. However, they tend to be higher in cost, and cannot sustain their structural integrity when subjected to high temperatures (Modor Plastics, 2017) [52].

2.6.2. Phenolic Resins

Figure 2.8 - Epoxy Phenolic Resins.

Source: Cherry Paints & Polymerts Pvt. Ltd. (2016) [F8]

Phenol formaldehyde resins (PF), referred to as phenolic resins, are artificial polymers prepared from the reaction of phenol with formaldehyde. While these phenolic resins were mainly used in reinforced thermosets molded products, they are no longer considered their most important applications (Rodriguez et al., 2016) [53]. While FRPs utilized in structural elements mainly consist of carbon, glass, or aramid fibers, they are usually wrapped by epoxy, polyester, vinylester, phenolic thermosetting resins with more than 30% of fiber concentration is required (Bank, 2007) [54]. The speedy evolution and criteria enforced by the applications resulted in comprehensive researches that would improve and dictate better thermal characteristics of the synthetic resin (Bai, 2013) [4].

Currently, phenolic resins are utilized in almost every field ranging from regular to critical applications. Baeyer was the pioneer in his field whom reported phenolic-type resins as a formation resulting from the reaction among phenols and aldehydes through condensation during the 1870s (Economy and Parkar, 2011; Baeyer, 1872) [55,56]. The major shortcomings discovered during this early time was the foaming initiated that resulted from the discharge of formaldehyde throughout the reaction. Leo F. Baekeland resolved the latter issue through the utilization of fillers and pressure. Furthermore, his development continued in the early 1900s, which conveyed the formulation of the constituents from the fusion of resorcinol and formaldehyde through a process called polymerization (Economy and Parker, 2011; Baekeland, 1907) [56,57].

Reinforced polyesters in phenolic resins composites could present a promising future by enhancing their mechanical properties thru addition/modification of various reinforcing agents to create hybrid composites that are able to service for its desired function especially in structural applications where impact resistance is required. In addition, polyesters have reduced upkeep costs and could be efficiently refurbished and recycled in the duration of their lifespan. Consequently, they are renowned material that is commonly used in an array of applications such as the infrastructure construction and various other civil and structural designs (Ticoalu et al., 2010) [59].

A good example of hybrid composites can be achieved by mixing soft fibers (aramids and polyethylene) with carbon or glass fibers (Peijs et al., 1990) [60]. Considering the cost in mind, utilization of glass fibers instead of carbon fibers is deemed to be beneficial and more cost effective. However, carbon fibers are usually a more reliable reinforcing material in terms of flexural modulus. Thus, in structural applications, carbon fibers favored. Meanwhile, hybrid composites indicated a better wear resistance when used in severe environments such as marine and seawater structural applications (Friedrich et al., 1995) [61].

An even more significant capability concerning the thermoset polymer (resin) medium is that it ought to captivate energy along with minimizing tension forces accumulations through granting fracture sturdiness or plasticity to optimize damage allowance, as well as enduring robustness. Likewise, it should grant hot/wet functionality and efficiency. Vulnerability pertaining to the polymer-medium to water and the conforming decrement regarding hot/wet functionality across an aggressive natural surrounding is an issue. Persisted repetitive pattern due to dehydration to moist conditions could initiate trivial growth throughout the volume of the polymer (Pilato and Michno, 1994) [49].

The alternation of expansion/contraction of the resin matrix pertaining to such situations might generate micro-cracks. Hence, the matrix resin is anticipated to offer utmost composite qualities through the utilization of a recommended thermal degree concentration regardless of the said complications and difficulties. The preeminent thermo-mechanical capability attributes of the blended mix are regulated according to the elevated temperature pertaining to the thermoset polymers matrix (Pilato and Michno, 1994; Naebe et al., 2016) [49,139].

According to Bai (2013) [4], Phenolic thermosets happen to be inelastic thru ordinary climate conditions. Hence, they are favored in applications that necessitate desirable mechanical properties become needed. In addition, thermosets should be mixed using reinforcement to fortify and boost these particular characteristics. Synthetic composites formed on thermoset matrices could replace metal reinforcement as well as concrete itself in a number of uses in civil projects due to the fact that their greater resistance to corrosion compared to steel/metal.

Furthermore, they tend to acquire greater freeze-thaw resistance in comparison with cementatious products. Moreover phenolic mixes could be manufactured using sophisticated forms while having a vigilant design style, components could be acquired with high strength, stiffness, and superb collision bearing resistance, resulting in products that are able to substitute steel and metal reinforcements. However, phenolic thermosets are considered inelastic composites that retain sufficient mechanical characteristics. In order to overcome the latter concern, thermosets shall be reinforced with materials that achieves the demanded properties and shall be of cross-links nature that would allow the phenolic resins to be utilized at greater temperatures (Paiva and Frollini, 2000; Bai, 2013) [65,4].

Since the materials used in construction necessitate the ability to resist fire and excessive temperatures, the constituents that shall be used as well as moldings laminates formed on phenolic resins must retain such properties. The laminates are able to resist burning with nominal fumes and poisonous smokes, especially during the manufacturing process. Hence, phenolic composites could favorably influence the construction sector by enhancing their safety, durability, as well as lowering the production cost of construction constituents by substituting cement with polymers (Tyberg et al., 1999) [66].

In order to understand resin characterization based on the preferred thermoset, they shall endure few molecular weight improvements since thermoset composites are always in solid-state. Contrast to polymers, oligomers consist of only a limited amount of monomers, and while thermoset resins are low molecular weight oligomers, it is essential to perform improvements on their molecular weight (MW) to properly disperse the fibers within the implantation process (Naka, 2014) [78].

Despite the product significance, as well as the challenging competition result from thermoplastic resins, thermosets sustained their prominence and are still used in numerous engineering applications (Kotsilkova, 2007) [79]. This is due to the properties obtained from Phenol Formaldehyde (PF) which offered exceptional flame resistance, trivial smoke dispersal, plus the nominal toxicity discharge upon ignition, PF are undergoing a revival in their significance as an advanced composite material especially in aircraft and freight ships interior (Kozłowski and Władyka-Przybylak, 2008) [80]. Similarly, ACMs gained a vast recognition in the aerospace industry and are currently being used in many aircraft’s exterior structural elements. Table 2-1 below illustrates the utilization of ACMs in some of the modern aircraft:

Fighter Aircraft (US)	F-16, F-14, F-18,YF-23, F-22, JSF, UCAV.
Fighter Aircraft (Europe)	Gripen JAS-39, mirage 2000, rafael, eurofighter typhoon, lavi, DASA Mako
Fighter Aircraft (Russia) Bomber (US)	MiG-29, su series B-2
Transport (US)	KC-135, C-17
Transport (US-commercial)	B-777, B-767, MD-11
Transport (Airbus, European)	A-320, A-340, A380, Tu-204, ATR42, Falcon 900, A300-600 ST
General aviation	Piaggio, Starship, premier 1
Rotary aircraft	V-22, Eurocopter tiger, comanche, RAH-66, bell/agusta BA-609, EH101, super Lynx 300, S-92.

Table 2-1 - Aircraft Composite Materials Usage

Source: Udupa et al. (2014) [81]

Additionally, the resins are the ideal option in high performance ballistic composite modules that either include S-2 Glass or Kevlar aramid fibers. Even though Baekeland did not know phenolic resins in terms of the macromolecular order, he definitely offered a vital impact towards the establishment of the plastics manufacturing sector (Baekeland, 1909; Pilato and Michno, 1994; Economy and Parkar, 2011; Bai, 2013) [62,49,55,4]. Different resin systems can be used to attain the polymer matrix. The below table compare the pros and cons of thermosetting vs. thermoplastic resin systems:

Component	Property	Thermoset	Thermoplastic
Resin	Formulation	Complex	Simple
	Melt Viscosity	Very Low	High
	Fiber Impregnation	Easy	Difficult
	Cost	Low to Medium	Low to High
Prepreg	Tack, Drape	Good	None to Fair
	Stability (Shelf Life/Out Time)	Poor	Excellent
	Quality Assurance	Fair	Excellent
Composite	Processing Cycle	Long	Short to Long
	Processing (Time/Temp/Pressure)	Low to Moderate	High
	Fabrication Cost	High	Low (Potentially)
	Structural Properties	Fair to Good	Fair to Good
	Environmental & Solvent Resistance	Good to Excellent	Poor to Good
	Interlaminar Fracture Toughness	Low	High
	Damage Tolerance	Poor to Excellent	Fair to Good
	Data Base	Large	Small

Table 2-2 - Composite Properties Based On Thermoset vs. Thermoplastic Resins

Source: Pilato and Michno (1994) [49]

In order to decide on whether thermoset or thermoplastic resins must be used, a close examination and evaluation of these resins in terms of their strengths and weaknesses shall be performed. Finally, the optimal option shall incorporate the material and its alteration into prepreg by integrating strengthening fibers as well as the fabrication and ease of handling of the produced material (Pilato and Michno, 1994) [49].

2.6.2.1. Phenolic Resins and Glass Fibers

Ever since its discovery, glass fiber acquired vast recognition in typical applications as a chief constituent used in composites. According to Wallenberger et al. (2001) [63], glass fibers are classified into two classes, The most common is the low cost general purpose type of glass fibers, whereas the premium type of fiber glasses are fabricated to attain specific properties based on the necessitated application criteria.

The standard low-cost glass is perceived as "E Glass" and comprises of calcium alumino-borosilicate structure and acquires low electrical conductivity. On the other hand, the specific-purpose glass fibers differs based on the application’s purpose, such as A-Glass known as Alkali-lime glass fiber which acquires high alkali or soda lime within the fiber structure, S-Glass which acquires high strength, E-CR

Glass which possesses resistance towards chemical and electrical attacks, C-Glass which resist chemical attacks, M-Glass which acquires high stiffness properties, D-Glass that comprise of low dielectric constant, and lastly R-Glass that possesses elevated mechanical properties (Wallenberger et al., 2001) [63]. Table 2-3 below illustrate the various mechanical properties of glass fibers based on their composition:

	Advantex	AR glass	C glass	D glass	E glass	E-CR glass	R glass	S-2 glass
Density g/cc. ASTM D1505	2.624	2.70	2.52	2.11	2.55-2.62	2.68-2.72	2.54	2.48
Refractive Index	1.561	1.562	1.533	1.465	1.558	1.574-1.576	1.546	1.521-1.525
Softening point °C		773	750	771	846	882	952	1056
Strain point °C	691		522	477	610-630		736	766
Sp. heat cap. J/g°C			0.787	0.733	0.810		0.732	0.737
Thermal exp. coef. ppm°C	5.8	6.5	6.3	2.5	5.4	5.9	3.8	1.6
Dielectric strength kV/mm	10.12				10.4-10.6	9.84	10.8	13.0

Table 2-3 - Glass Fiber Properties by Composition

Source: Kinsella et al. (2001) [64]

However, since the requirement is based on the tensile strength properties to be utilized in structural applications, the glass fiber consideration shall be on the S-Glass type. Meanwhile, the technological advancement occurred in the period following the 1990s allowed the utilization of micro and nano-scale fiber reinforcements. As a result, glass fibers become commonly used in the reinforcement of the phenolic composites. They are mainly composed of continuous filaments having various thicknesses and their properties differ by the form/type of glass used (Frollini and Castellan, 2012; Pilato and Michno, 1994) [19,49].

Phenolic composites that contain glass fibers elements possess excellent characteristics in terms of flammability and fire resistance, whereas the smoke and carbon monoxide generated is trivial upon exposure to heat. Such qualities presented by the phenolic-glass fibers made it ideal for the production and utilization of structural flooring, ceiling panels, as well as aircraft and storage compartment interiors (Mouritz, 2006; Bai, 2013) [67,4].

However, these phenolic glass-reinforced fiber composites such as E-glass FRP are only deemed useful in non-stressed applications, whereas pre-stressed applications necessitated the utilization of carbon fibers (CFs). On the other hand, glass-fibers acquire a greater level of vulnerability to creep rupture at inferior stress intensities compared to CFs. Meanwhile, CF demonstrate little to no chemical-stimulation strength deprivation, while acquiring more extent in median failure times subjected to stress rupture situations as illustrated in Table 2-4 below (Chiao and Moore, 1971; Chiao et al., 1972; Moore et al., 1974; Karbhari et al., 2003) [68,69,70,71]:

Fiber Type	10% Failure probability stress rupture level after 75 years (%)	Spread in median time to fail in decades
Carbon	75	6
Aramid	60	3
Glass	50	2.5

Table 2-4 – Fiber Stress Rupture Level for 10% Population Failures
After 75 Years Continuous Stress Exposure Under Ambient Conditions

Source: Karbhari et al. (2003) [71]

According to GangaRao et al. 1999; Harik et al. 1999; Temeles et al. 2000; Davalos et al. 2001; Russel, 2003; Bakis et al., 2002 [72,73,74,75,76,58], many constructed infrastructures, such as FRP bridge-decks, are erected utilizing glass-reinforced fiber composites. The latter is due to the outstanding performance results obtained by these bridges. As a result, many designers prefer to substitute steel reinforcement with glass FRP. The utilized product is referred to as Glass Fiber Reinforced Concrete (GFRC).

However, the alkalinity in glass-fibers concrete can cause an immense damage to the fibers due to several methodological factors ranging from pitting, hydroxylation, hydrolysis, and leaching (Karbhari et al., 2003) [71]. In addition, challenges are faced in connections of adjoining panels and links, fatigue caused by static and cyclic stresses, endurance and reliability under various loading conditions, breakdown and deficiency of the composite, various defects and microscopic flaws that affects the ultimate strength, buckling modes of failure, and delamination and deterioration of joined layers. Modern technological advancement and researches in FRP resulted in overcoming many of these challenges, which confirms the high potential in utilizing Glass-FRP in diverse applications (Bakis et al. 2002) [58].

Thus, phenolic composites could favorably influence the construction sector through increasing the durability and lowering costs. They are considered a primary substitute for structural component's development, such as FRP bridges (as stated earlier). Nowadays, the availability of various procurement methods offers the designer the freedom and flexibility to create various structural elements in diverse forms/styles. Since phenolic/glass composites possess characteristics such as fire resistance, and low thermal conductivity, therefore, it results in abolishing the requirement for mineral components and hence, decreasing the overall weight of the designed structural elements (Forsdyke, 2002; Bai, 2013) [77,4].

2.6.3. Prepreg

Prepreg is defined as a fibrous product that is pre-infused with resin (usually referred to as reinforcing fabric as shown in Figure 2.9 below), which could be natural or synthetic, that is become the standard technology in the production of High Modulus Reinforced Composites, such as FRPs. The systems fabricated based on the high modulus reinforced composites/matrix resins could be any of thermoset or thermoplastic. Meanwhile, the fiber used could be one- or multidirectional tape or interlaced textile-form (Bai, 2013) [4].

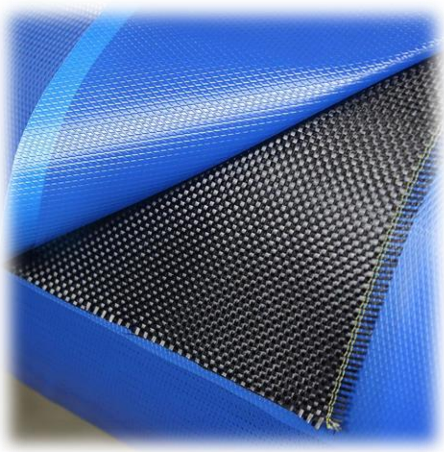


Figure 2.9 - Reinforcing Carbon Fiber Prepreg (Fabric)

Source: Fibre Glass Development Corporation (2016) [F9]

Pilato and Michno (1994) [49] identified the recognized qualities of the advanced composite material and characterized them based on the embedded fibers and strengthening agent properties. In order for the produced ACMs to be accepted, embedded fibers shall maintain high strength (2-7 Gpa) with a low dense (950-2500 kg/m^3) high stiffness and young's moduli (70-800 GPa). Therefore, the only fibers that can be utilized for structural applications are ultra high molecular weight polyethylene (UHMWPE), aramids, T-1000 (carbon) fiber (CF), S-2 glass, plus the recently recognized fibers known as PBO (Zylon, or Polybenzoxazole) and PBT (Polybutylene Terepthalate, or Polybenzothiazole). While the S-2 glass fibers modulus does not meet the minimum requirement, it can be accepted for usage in structural applications due to its high specific strength. Table 2-5 below provides a brief on the properties and characteristics of HPFs (Pilato and Michno, 1994) [49].

Fiber	Density kg/m^3	Tensile strength (GPa)	Specific strength (10^6 cm)	Tensile modulus (GPa)	Specific modulus (10^8 cm)	Compressive strength (GPa)	Elongation %
UHMWPE	970	3.0	31	175	18	0.17	3.0
KEVLAR	1440	2.6	18	60–200	4.2–14	0.34–0.48	3.8
TECHNORA	1390	3.0	21	70	5.0	—	4.4
PBO	1580	5.7	36	360	23	0.2–0.4	1.9
PBT	1580	4.1	26	325	21	0.26–0.41	1.1
Pitch CF	1600–2200	0.8–2.3	5–10	38–820	2.3–38	0.48	0.25–0.50
PAN CF	1700–1900	2.3–7.1	14–37	230–830	13–26	1.05–2.75	1.5–2.4
S-2 Glass	2490	4.6	19	85	3.4	1.1	5.7

Table 2-5 - High Performance Fiber Properties.

Source: Pilato and Michno (1994) [49]

According to Bai (2013) [4], fiber reinforced composites have high stiffness to-weight ratio, however this proportion might be boosted if, rather than a solid form, two thin composite face-sheets of a similar mass, such as plastics embedded with CF's, with a cellular core form in between (usually a Nomex honeycomb), are utilized. The latter is frequently employed in applications where reduction in weight is needed. Furthermore, it is also utilized in applications where fire safety requirements are high, such as airplanes and train manufacturing. Meanwhile, high performance fibers tend to achieve high specific strength and moduli. Accordingly, they are currently being used in variety of applications covering all aspects of our daily life. Applications of these fibers include essential fields such as electrical, mechanical, structural and many others through the composite products being procured with them. The latter is especially vital in ACM related applications, as they usually require high tensile and compressive strength, modulus, and rigidity.

2.6.4. Ultra High Molecular Weight Polyethylene (UHMWPE)

UHMWPE is a type of thermoplastic polyethylene that is greasy-alike and possess a vast resistance to corrosive chemicals. Typically, UHMWPEs are not affected by various environmental conditions, such as moisture and abrasion due to their lubricating nature. Accordingly, their lubricating and frictionless nature contributes towards gaining an exceptional impact resistance compared to other plastics (Pilato and Michno, 1994) [49].

Since the requisite is to produce high strength fibers, high molecular weight polymers (HMW) can be employed to procure HPFs utilizing various types of fibers, which could either be Polyethylene (PE), Polypropylene (PP), Polyvinyl Alcohol (PVA), or Poly-acrylonitrile (PAN). However, in order to fabricate the UHMWPE composite, the fibers that must be used must be falling within the High Performance-Polyethylene Fibers (HP-PE) category, whereas the fibers must achieve outstanding tensile strengths reaching up-to 5 GPa and 200 GPa modulus (Pennings et al., 1984; Pilato and Michno, 1994) [82,49]. Hence, UHMWPE composites exhibit a credible solution to diverse structural applications ranging from aerospace to auto parts to medical body implants such as artificial bones, as well as various civil structural uses. Even in the food industry, UHMWPEs are being utilized as they prevent the growth of fungus and bacteria due their plastic structural form (Wang et al., 2005) [83].

In general, polyethylene fibers are procured in many forms. However, the most common forms are the high performance, the high-modulus, and the extended chain polyethylene fibers (HPPE, HMPE, and ECPE respectively) (Hearle, 2001) [84]. Consequently, these properties that can be attained by the utilized fibers results in an excellent potential for UHMWPE utilization in civil structural elements as it could prolong the service-life of newly constructed structures significantly. The latter can be accomplished through the deployment of particular forms of Carbon Nanotubes

(CNT's) that can be procured directly from Ultra High Molecular Weight Polyethylene (UHMWPE).

2.6.5. Aramid Fibers (AF)

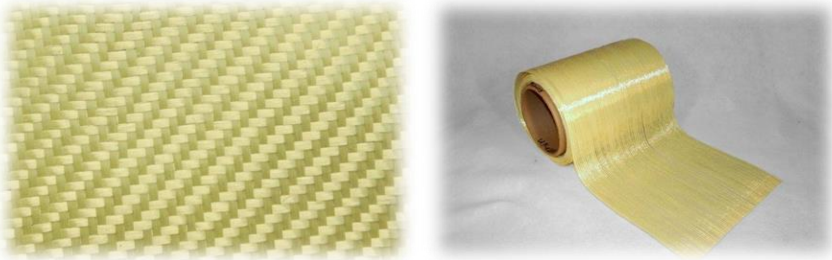


Figure 2.10 - AR Composite Fabrics. Woven (Left), and Nonwoven Aramid Fabrics (Right)

Source: ACP Composites (2016) [F10]

Aramid fibers, or high strength aromatic polyamides, are products of polyamides. Polyamides were first discovered during the early 1920's. However, the early production of fibers that are based on polyamides commenced in 1928. Wallace Carothers along with DuPont team members were considered the pioneers that initiated this vital research program by commercializing nylon fibers in the early 1930s (Kauffman, 1988; Pilato and Michno, 1994 [128,49]) [128,49]. Aramid fibers were first commercialized back in 1971 and are referred to as DuPont's Kevlars. These fibers acquire high strength, modulus, and resistance towards absorption, organic solvents, and corrosion. In addition, they are considered a stable material chemically and mechanically under an extensive variety of temperatures (Chiao and Lubin, 1982) [85]. The reason that the aramid fibers are considered valuable is due to its high thermal and electrical properties. Similarly, aramid fibers can be formed into various shapes and sizes, and can be utilized in a various types of composite materials. As a result, their applications are limitless, whereas the fibers can be used in almost any application that requires reinforcement (Fibermax Composites, 2017) [86].

2.6.6. Carbon Fibers

Figure 2.11 - Carbon Fiber

Source: Craftech Industries (2017) [F11]

Carbon fibers are high performing fibrous materials that attain excellent physical and mechanical properties such as: high strength to weight ratio, outstanding tensile strength, and exceptional rigidity with an excellent corrosion, fatigue, and fire resisting material (Verma and Netula, 2017) [87]. Since its discovery back in the early sixties, Carbon fibers (CFs) gained a wide global recognition and became the most commonly utilized reinforcing material in advanced composite systems. CFs can be manufactured in various profiles and are deemed to be a strong product that acquires a high modulus and is capable to resist and reduce deterioration rate on structures subjected to various stresses and environmental factors. They facilitated exceptional improvements in almost every field such as, but not limited to: aerospace, armory and weaponries, aerial equipment, railway industries, automobile brakes, civil and structural engineering, industrial engineering, mechanical engineering, nuclear fields, medical equipment, as well as various other industries (Donnet and Bansal, 1998) [88].

In structural engineering, Carbon fibers are considered an excellent construction and repairing material to be used in deteriorated concrete structures. Furthermore, they retain exceptional characteristics in terms of vibration damping, overall molecular weight, and oxidization resistance. It is vital to note that carbon fibers in civil structural engineering are usually identified based on their tensile performances and rupture behavior. While tensile strength of CF is the key aspect criteria for structural applications, it is not considered the only factor affecting the evaluation of the fiber strength, rather, the consideration is presenting that all three factors are essential, namely: modulus, tensile and compressive strength are equally important (Mallick, 1997) [29].

Many researches dealt with CFs in terms of its formulation, enhancing strength, and testing of a wide range of strong fibers involving carbon or graphite fibers (Watt and Perov, 1985) [89]. However, in order to further understand CFs performance, they shall be analyzed on the basis of its three polymer's origins known as precursors [Cellulosic (rayon), Acrylic (poly (acrylonitrile) or PAN), and mesophase pitch] (Pilato and Michno, 1994) [49]. The properties of the CF produced can vary vastly based on the regulating precursor, as well as the manufacturing process and surrounding conditions. These precursors control the manufacturing businesses depending on the application criteria that necessitate distinctive mechanical and physical characteristics (Frank, Steudle, and Ingildeev, 2014) [90].

Thus, carbon fibers are procured from either Cellulosic, Petroleum-based Pitch, or Acrylic precursors referred to as PAN (Poly-acrylonitrile). While all three precursors would yield the attainment of carbon fibers, every material possesses different properties than the other (Frank, Steudle, and Ingildeev, 2014) [90].

2.6.6.1. Rayon Precursor (Cellulosic-based)

Rayon precursor is produced from naturally occurring cellulose polymers (Regenerated Cellulose). They are widely available material that is cost efficient and easy to fabricate. They are usually procured in the form of fabric. The thermal treatment of the Rayon Precursor results in a low modulus Carbon Fiber (usually around 50 Giga-Pascal). The modulus of the precursor is determined by the amount of carbon fibers utilized in its production. In the case of Rayon Precursor, the typical amount used is around 44.4 % CF of the Rayon (Bhat et al, 2013; Park and Heo 2015) [91,92].

The vital elements to attain a high efficiency level in these applications comprise of reduced heat transmission rate, low molecular weight, high physical thermal constancy and carbon rate. Furthermore, performance of these applications relate directly to tensile strength, availability of sodium within the fibers, as well as adequate modulus for attaining applicable structural stability. Table 2-6 presents the typical properties of rayon-based Thornel carbon and graphite fibers and fabrics (Pilato and Michno, 1994) [49].

Material precursor product weave	Carbon rayon			Graphite rayon	
	VCK 5HS	VCL 8HS	VCX-13 5HS	WCA plain	
Total fabric properties					
Width, m		1.09–1.14	1.07–1.14	1.09–1.14	1.07–1.15
Weight, g/m^2		254.3	271.2	254.3	244.1
Gage (thickness)-mm		0.457	0.508	0.457	0.559
Count, Yarns/mm	Warp	1.57	2.09	1.57	1.14
	Fill	1.42	2.05	1.42	0.83
Filaments/Yarn bundle		980	720	980	1470
Carbon assay, %		99 +	97.0	99.5 +	99.9
Ash content, %		0.30	0.40	0.08	0.01
Tensile, kg/m	Warp	625.0	803.6	625.0	892.9
	Fill	535.7	803.6	535.7	357.2
Electrical resistivity	Warp	0.45	0.60	0.45	0.38
(ohms/square)	Fill	0.46	0.56	0.46	0.53
Density, kg/m^3 (ASTM D-3800)		1500	1520	1470	1440
Typical yarn properties					
Water adsorption capacity %		2	13	1	0.1
Strength, GPa		0.69	0.69	0.69	0.69
Modulus, GPa		41.4	41.4	41.4	41.4
Electrical resistivity (u-ohm-m)		38	59	36	36
Thermal conductivity (W/m K)		4.0	3.7	4.1	4.1

Table 2-6 - Typical Properties of Rayon-Based Thronal Carbon and Graphite Fibers and Fabrics

Source: Amoco Performance Products Inc., Pilato and Michno (1994) [98, 49]

2.6.6.2. Mesophase Precursor (Pitch-based)

Pitch-based carbon fibers are fabricated using petroleum pitch (visco-elastic material) distillation process such as oil and coal using a four-step procedure, which are: Melt Spinning, Stabilization through Oxidization, Carbonization, and Graphitization of the precursor fibers. They are complicated mixtures of poly-aromatic molecules and heterocyclic compounds. In addition, they typically comprise of at least 80% carbon content that attains properties dependent on the source tar and processing settings (Berrueco et al., 2011; Park and Heo, 2015) [93,92].

According to Pilato and Michno (1994) [49], pitch-based carbon fibers exhibit extraordinary properties that allow these fibers to be utilized in major applications such as avionics. These fibers offer a desirable axial modulus (reaching upto 827 GPa), high thermal and electrical conductivity, as well as elevated thermal expansion resistance while preserving sufficient resistance towards applied tensile forces. The subsequent product retains ideal weight (lightweight), extensive rigidity and thermal conduction, structural constancy and significant strength. However, the downside of the high modulus pitch-based fibers is the modest ability to resist high compressive strength due to the microstructural variances of pitch fibers that are vulnerable to shear forces. Thus, these fibers and their respective composites are preferably used in structures where compressive strength is not essential. Table 2-7 below illustrate a few of the typical mechanical and thermal properties of high modulus pitch fibers:

Property[a]/Fiber	P-75	P-100	P-120
Moduli			
E_a, (GPa)	517	690	827
E_t, (GPa)	9	6.9	6.9
G_a, (GPa)	13	21	21
ν_a	0.23	0.26	0.3
ν_t	0.74	0.74	0.85
Strength			
σ^{tu}, (MPa)[b]	1900	2240	2240
σ^{cu}, (MPa)[c]	690	520	410
Thermal expansion			
α_a, 10^{-6}/K	− 1.46	− 1.48	− 1.50
α_t, 10^{-6}/K	12.5	12.0	12.0
Thermal conductivity			
K_a, (W/mK)	190	530	610
K_t, (W/mK)	2.4	2.4	2.4
Specific heat			
C, (kJ/kgK)	1.0	1.0	1.0
Density			
ρ, (kg/m^3)	2160	2160	2190

[a] subscript a = axial; subscript t = transverse; superscript t = tensile; superscript c = compressive; superscript u = ultimate

[b] representative data from strand and/or laminate tests

[c] estimated

Table 2-7 - Typical Mechanical and Thermal Properties of Ultra-High Modulus Pitch Fibers

Source: Amoco Performance Products Inc., Pilato and Michno (1994) [98, 49]

Due to the structure and significant performance of the pitch-based carbon fibers, they have acquired a recognizable attention towards manufacturing components for high-temperature based applications (Arai, 1993) [94]. Studies presented by researchers, such as Schulz (1987) [95], as well as Barr et al. and Bacon and coworkers (1982 – 1985) [96,97], investigated the properties of pitch fibers in comparison with various other fibers in terms of modulus, thermo-mechanical characterization, and thermal expansion properties presented rheological data that react due to plastic flow rather than deforming elastically to applied stresses.

The most common utilized fibers in the industry are the ultrahigh modulus pitch-based (K13D) and high ductility pitch-based (XN-05) (Naito et al., 2008) [118]. In general, utilizing the oil based pitch precursor would result in carbon fibers having exceptional modulus and ductility properties.

2.6.6.3. Acrylic Precursor (PAN-based)

According to Park and Heo (2015) [92], the firms manufacturing textile grade acrylic fibers invented the acrylic precursors for the production of carbon fibers. The carbon fibers were manufactured utilizing the pyrolysis of acrylic fibers. Accordingly, the produced carbon fibers from PAN-based carbon fibers have been commonly used as a reinforcing material in various mechanical, civil structural, and aerospace engineering applications. Thus, if high strength is required, then the PAN precursor shall be considered as an optimum choice.

According to Pilato and Michno (1994) [49], PAN-based carbon fibers generally have high strength, high modulus and low density (1.75–2.00 g/cm^3). In addition, utilizing PAN-based carbon fibers results in an ultrahigh tensile strength carbon fiber referred to as T1000GB (Naito et al., 2008) [118]. The higher tensile strength fibers are formed at the peak carbonization temperature during the procurement of the fiber. It is essential to note that PAN-based CFs acquire more compressive strength than Pitch-based CFs (Pilato and Michno, 1994) [49]. As stated earlier, temperature variations could result in different properties of the PAN-based fibers due to properties alterations of the PAN-precursors at different temperatures as shown in Table 2-8:

Temperature (°C)	P1			P2			P3		
	Titre (dex)	Tensile strength (MPa)	Elongation (%)	Titre (dtex)	Tensile strength (MPa)	Elongation (%)	Titre (dtex)	Tensile strength (MPa)	Elongation (%)
25 (Precursors)	1.14	633.6	10.8	1.63	533.5	11.7	1.24	578.5	10.6
125	1.17	633.7	10.8	1.61	533.6	11.7	1.24	578.5	10.6
192	1.13	561.9	10.8	1.59	584.9	12.2	1.24	596.4	11.2
202	1.14	567.8	11.0	1.42	565.5	11.9	1.25	581.3	11.3
214	1.09	544.1	11.4	1.61	413.7	11.6	1.26	682.2	11.8
222	1.09	500.2	10.7	1.60	409.7	12.1	1.26	573.8	11.2
231	1.07	491.6	11.4	1.48	419.0	11.3	1.19	602.9	11.4
240	1.18	431.4	11.6	1.52	379.9	13.3	1.24	484.6	11.6
253	1.11	400.1	12.1	1.46	323.0	13.0	1.24	525.8	11.8
268	1.06	355.7	13.5	1.39	287.7	12.6	1.20	486.1	11.9
277	1.02	342.3	15.7	1.35	247.6	10.7	1.18	410.4	13.0
283 (Preoxidized fibers)	1.06	231.6	13.6	1.39	246.5	12.0	1.18	316.4	11.5
428–603–803–1003	1.01	769.2	0.7	0.83	1189.1	1.2	0.85	1373.0	1.5
1350 (Carbon fibers)	0.87	2557.5	0.5	0.77	3507.1	0.8	0.83	3989.4[a]	1.1

Table 2-8 - The properties of PAN precursors
preoxidized and carbon fibers with the change of temperature

Source: Wangxi et al. (2003) [99]

Researches performed by Wagoner, Smith, Bacon, Kowalski, and Eckstein between 1987 and 1989 [100,101,102,97] investigated results and data of the production operations of CF from Amoco Performance Products, Inc. in South Carolina [98]. The methods of investigation to attain the required data of the CF properties comprised of values gained from single fibers or a collection of attached fibers. The attained data serve as an indicator or indirect measurement of the resulting composite properties and its potential applications in various fields. Table 2-9 below illustrates commonly PAN based CFs properties (Amoco Performance Products; Pilato and Michno, 1994) [98,49].

	T-300	T650-35	T650-42
Axial[a] tensile strength, (GPa)	3.65	4.55	5.03
Axial tensile modulus, (GPa)	231	248	290
Density, (kg/m^3)	1760	1770	1780
Filament Diameter, (μ)	7	6.8	5.1
Elongation at break, (%)	1.4	1.75	1.7
Carbon assay, (%)	92	94	94
Surface area, (m^2/g)	0.45	0.5	0.5
Axial thermal conductivity, (W/mK)	8.5	14	15
Electrical resistivity, (μ ohm-m)	18	14.9	14.2
Axial CTE at 21 °C, (ppm/°C)	− 0.6	− 0.6	− 0.75

[a] Axial and longitudinal are used interchangeably throughout.

Table 2-9 - Typical Properties of Thronal PAN-based Carbon Fibers.

Source: Pilato and Michno (1994) [49]

2.6.6.4. Summary of Carbon Fiber Precursors

The properties of PAN, Pitch, and Rayon Precursors are presented in Table 2-10 below:

Property	Rayon	Pitch	PAN
Fiber Diameter (microns)	10 to 11	5 to 8	6.5
Specific Gravity	2.0 to 2.2	1.71 to 1.96	1.7
Tensile Modulus (GPa)	170 to 980	230 to 595	415 to 550
Tensile Strength (MPa)	2275 to 4060	1925 to 6200	2070 to 2760
Elongation at Failure (%)	0.25 to 0.70	0.40 to 1.20	0.90 to 1.10
Thermal Conductivity (W/mK)	120 to 1100	10 to 25	3.5 to 4.0

Table 2-10 - Properties of PAN, Pitch, and Rayon Precursors

Source: Desai, D. (2017) [103]

2.6.6.5. Bonding of CF with the Matrix Resin

Katz et al. (1995) [104] identified carbon fibers do not posses the ability to bond properly with the composite mix. Although the performance and partial attachment strength of carbon-fibers are determined by its orientation, crystallinity, and defects content, the rest of the binding capability is undertaken by the binding additives embedded within the cement matrix. Thus, the utilization of binder additives to the cement is required to ensure adequate attachment of fibers to the cementitious matrix. Accordingly, the water-to-binder (w/b) ratio along with the content of silica fumes are the primarily factors affecting the bonding fibers to the cement matrix. Furthermore, the sizing of the utilized fibers affects the overall workability in the production of the desired composite. Therefore, the more the bonding level is increased in the composite results in a superior composite that acquires higher strength and toughness.

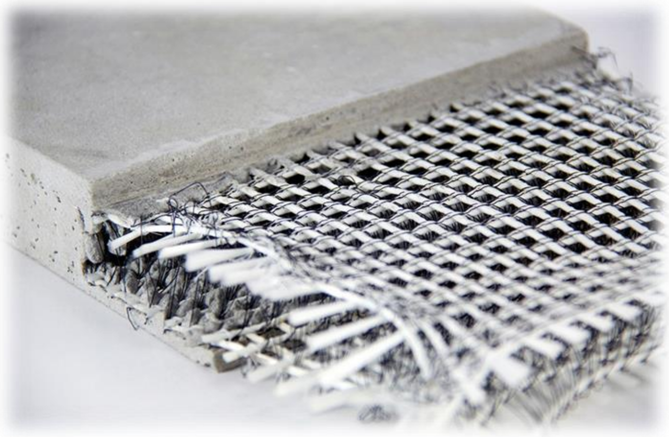


Figure 2.12 - Carbon Fiber Reinforced Concrete

Source: Thyroff, R. (2017) [F12]

The chemical bonding of the fibers with the composite matrix becomes stronger and a better end-use product is attained. Therefore, the structural performance of carbon fibers within a composite relies on: orientation (degree of alignment of graphite layer planes with the fiber axis and can be measured using X-ray diffraction), crystallinity (embedded crystal purity levels and sizes and can be measured using X-ray diffraction), and defects accrued within the fiber broken filaments (both internal and external defects), water-to-binder ratio, and level of silica fumes/blastfurnace slag content. Employment of the latter could result in extending the durability and eventually the service life of the structure (Mindess et al., 2003) [105].

In order to fabricate better CFs, Park and Heo (2015) [92] suggested regulating the production process give better orientation, crystallization, and defects content values. Accordingly, the polymer processing process regulates the fiber orientation, as well as the level of fiber spinning, drawing and thermal treatment applied into the fiber. On the other hand, the degree of crystallinity is controlled by chemistry of the original polymer the carbon fiber was procured from known as the precursor (as previously defined). Meanwhile, the level of thermal treatment applied on the precursor controls it as well. However, the level of defects is mainly regulated by the degree of purity of the original polymer, proper management of the procurement process, as well as applying suitable shielding on the polymer during production.

On the other hand, an investigation that was carried out by Fu et al. (1996-1998) [106,107] developed a method to further improve the bond strength significantly between carbon fiber and cement through the utilization of oxidizing chemical treatments with ozone treatment. The research yielded that polymeric admixtures such as latex and methylcellulose could also enhance the bond strength. The outcome was complemented by an expansion in the contact electrical resistivity of the interface as illustrated in Figures 2.13 and 2.14 below:

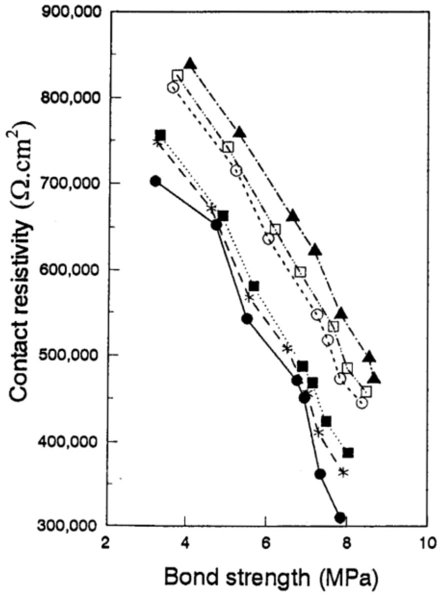


Figure 2.13 – Variation of contact electrical resistivity with bond strength for plain cement
in contact with as received (●) and five types of treated carbon fibers: Acetic Acid(*), H202 (■), NaOH (**O**), Nitric Acid (▫) and O_3 (▲).

Source: Fu et al. (1996) [106-107, F13, F14].

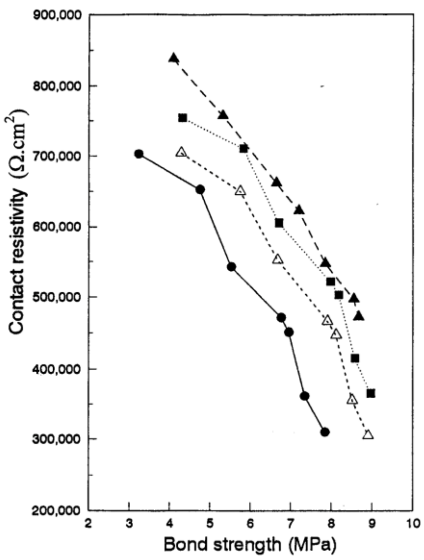


Figure 2.14 – Variation of cont. electrical resistivity with bond strength for as-received CFs
in contact with plain cement (●), cement with methylcellulose (Δ), and cement with latex (■). Also shown is that for O_3 treated fiber in contact with plain cement (▲).

Source: Fu et al. (1996) [106,107, F13, F14].

Consequently, CFs was believed to be a sustainable alternative to steel reinforcement in construction. Additionally, CFs retains outstanding performance in terms of thermal and electrical conductivity, friction, and bonding with the designed material matrix. Due to the excellent characteristics possessed by CFs, the aerospace industry presented a significant role in the development of aerospace industry (Choi et al., 2000; Frollini and Castellan, 2012; Bai 2013)[108,19,4].

Advancement in CF production techniques and methods resulted in higher quality carbon fiber with less flaws, and better tensile, compressive, and modulus properties. As a result, composites that utilize CFs offered a wide variety of applications in terms of structural needs. Similarly, concerns related to sustainability have necessitated the utilization of Carbon Fiber Reinforced Plastics (CFRP) and Carbon Fiber Reinforced Concrete (CFRC, Figure 2.15) in the construction industry as they retain substantial power in terms of seismic resistance (Ogawa, 2000) [109]. Nowadays, most retrofits in the construction industry that is subjected to seismic forces utilize carbon fibers as either plates (for retrofitting of slabs) or jackets (for retrofitting of columns). Furthermore, the construction industry utilizes various structural profiles that are created from Fiber Reinforced Plastics Composites specifically in buildings and infrastructure projects (Bakis et al., 2002) [58].

Figure 2.15 - Carbon Fiber Reinforced Concrete (CFRC).

Source: Shury, J., V. FRAAS Solutions (2013) [F15]

Phenolic composites having carbon fibers embedded within the matrix can be utilized for load-bearing materials as they posses extraordinary endurance to spasm, as well as working along with other fortifying materials once lubricants are applied. However, in order to avoid failure and overcome the low thermal properties in phenolic thermosets, utilization of CF within the matrix can be considered as an excellent material (Kim et al., 2009) [110]. On the other hand, other exceedingly aligned fibers such as Aramids are utilized in the phenolic resins in order to generate high performance composites for military applications (Gardziella et al., 2000) [111].

2.6.7. Carbon Nanotubes (CNTs)

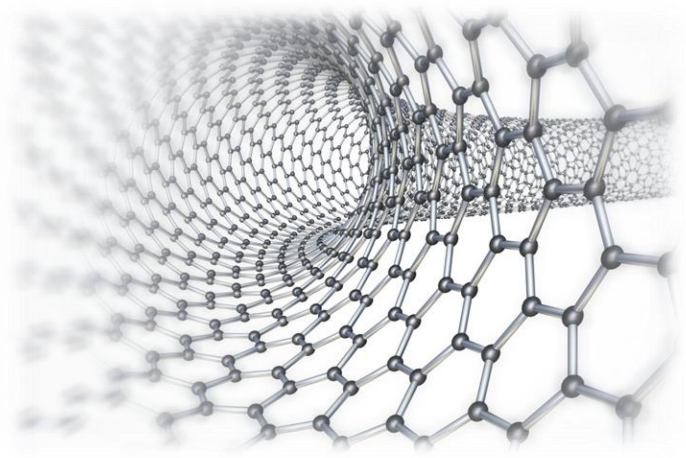


Figure 2.16 - Illustration of a Carbon Nanotube

Source: Tarantola, A. (2015) [F16]

Realized in 1991, Carbon nanotubes (CNTs) were first introduced by Iijima [116]. They consist of exceptionally tough hollow threads of carbon molecules that are interconnected in a tube form. Similar to that of graphite, CNTs are vastly isotropic. CNTs can be implanted in the concrete matrix like the steel rebar that empowers modern construction in numerous ways by providing a stronger, and much more durable and sustainable constructions. (Breuer and Sundararaj, 2004) [112].

According to Damolini (2009) [113], Carbon nanotubes attain excellent Young's modulus and tensile strength that are much stronger than steel reinforcement. These ultra-strong cables can resist excessive stresses imposed due to their ultra-high tensile strength. Therefore, they can be used as a substitute to typically used steel reinforcement and had been utilized extensively in long span and suspension bridges.

Although CNTs present remarkable inherent properties, reinforced mixtures could demonstrate inferior properties than anticipated. Furthermore, as nanoscopic components are employed in the production of extensively long cables in long span and suspension bridges, it is challenging to attain the actual strength and resistance capability of CNTs. In addition, defects in production and procurement could affect the properties of the material significantly. Consequently, CNTs shall be procured based on the application's requirement. (Breuer and Sundararaj, 2004; Damolini, 2009) [112,113].

Investigations and researches continued to develop CNTs in various aspects like carbon fibers, graphite foil, carbon pads, and carbon fabric. Nowadays CNTs are being affiliated with the progress in various fields and arenas and are no longer exclusive to the structural engineering field.

2.6.8. Particulate Composites

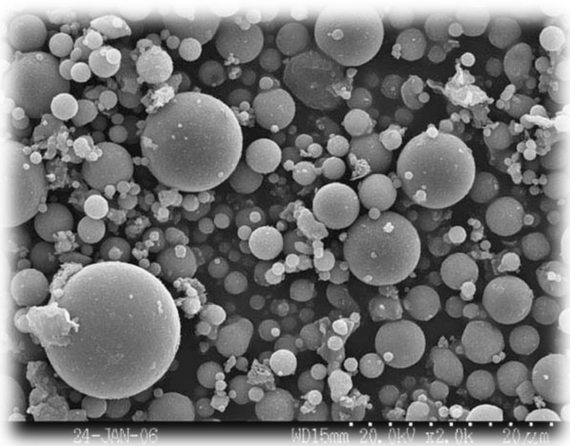


Figure 2.17 – Flyash used in Particulate Hybrid Polymer Composites

Source: University of Kentucky (2017) [F17]

As stated earlier, another form of composites is the particulate composites or also known as particle-composites. This type of composite is considered an innovative form of the advanced composite materials (ACMs) that is commonly used in the rehabilitation, repair, and retrofitting of deteriorated concrete structures. Nowadays, many forms of particulate polymer composites are being utilized in newly built structures as well, such as flyash, epoxy and various other types of particulate material. Nowadays, most deteriorated structures are getting repaired by either micro-concrete particulate composites, specifically in areas where aggressive weathering and soil conditions is present such as the case in the Arabian Gulf region or by fiber-reinforced plates (slabs) and jackets for the (columns).

Since the early 90’s, it had long been noted that micro-concrete particulate composites are being used in the repairing, retrofitting, and rehabilitation of various kinds of deteriorated concrete structures. While micro-concrete deemed an efficient solution for the repairing of such structures, many challenges arose out of its utilization, such as the competency of applicators, efficiency of composite to prolong the service-life of the structure, and most importantly, the life-cycle cost and sustainability of employment of this type of ACMs.

On the other hand, intensive researches were performed towards the advancement of particulate phenolic composites in the civil structural field. They are recognized as the principal aspect that fostered the invention of Polymer Portland-Cement Concrete (PPCC) or Polymer Cement Concrete (PCC). The latter revealed that the utilization of polymers in concrete could further develop the conventional used concrete. Consequently, many papers that were published evaluated the possibility of implementing, improving, and possibly replacing the Portland Cement Concrete.

2.6.9. Polymer Cement Concrete

Figure 2.18 -Polymer Concrete

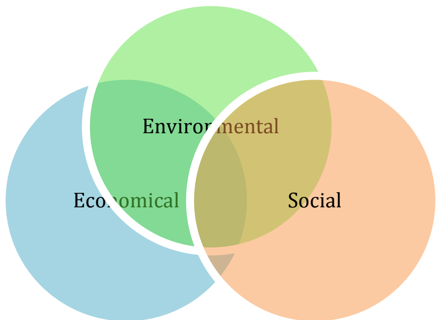
Source: Padhi, S. (2014) [F18]

As stated earlier, phenolic concrete composites were initially developed through the amalgamation of conventional Portland Cement Concrete with Polymers to form Polymer Cement Concrete (PCC), later referred to as Polymer Concrete (PC) or Polymer Modified Concrete (PMC). Polymer concrete (PC) is a composite material that is produced through the polymerization of a combination of monomer/aggregate in the matrix resin. This type of concrete acquires excellent mechanical properties such as high compressive and specific strengths. In addition, it exhibits great endurance against various chemical attacks (Bedi et al., 2013; Bedi et al., 2014) [114,115].

Nonetheless, the continuous expanding research in PCC formed the base for further advancement in terms of concrete polymers through the impregnation of low viscous monomer into the Polymer Cement Concrete to form Polymer Impregnated Concrete, referred to as PIC. The latter offered greater structural and durability properties compared to PCC. While the process for impregnation is complex and costly, it is comprehended to compensate for the higher cost in terms of long-term durability. Furthermore, PIC acquires outstanding physical and mechanical properties that have resulted in considering this type of concrete as a potential substitute to normally reinforced concrete (Shariatmadari, 1991) [117].

According to Bedi et al. (2013) [114], investigations on polymers and impregnation processes resulted in the discovery of Polymer Concrete (PC), also known as resin concrete. This type of concrete is a result of polymerization of monomer and aggregate combined in the matrix resin, whereas the polymerized monomer (that could be organic or inorganic) performs as the connecting mediator instead of cement. The replacement of cement by the polymerized monomer yields superior concrete properties to that of the conventional concrete. Polymer Concrete is a low-weight product that acquires exceptional compression and tensile strengths, as well as high resistance to moisture and various chemical attacks. However, attention must be paid in the choice of the polymerized monomer as each type of monomer attains particular properties than are than other monomers. The rising interest in Polymer Concretes (PCs) originated from the necessity to repair deteriorated concrete structures due to its unique ability resist various ingress attacks initiated by water/chemicals and its ability to be cured rapidly.

2.7. Restoration of Structures and Sustainability



Due to the ecological, economical and sustainability concerns, the importance of producing composites that would restore diverse structures instead of constructing new ones and consuming more scarce resources arose (Gemert et al., 2001) [119]. The life cycle of structures is composed of three principal phases, the production, construction, and operational stages that necessitate a vast consumption of energy and natural resources. Once the service-life of the structure is exceeded, the constructed structure requires demolition and reconstruction. However, utilizing composites in the construction stage results in extending the service-life of the structure immensely.

Meanwhile, yet another challenge was faced in the raw materials that are used in the manufacturing of the phenolic resins as the materials are being acquired from non-renewable origins. Thus, the introduction of bio-based resins would serve better and is considered inexpensive and ecofriendly (Ramires et al., 2010a; Bai, 2013) [121,4].

2.8. Advanced polymers for new applications

Usually, polymers are known to disintegrate upon exposure to elevated temperatures. This indicates that constituents produced using polymeric mixtures should include fire-retardants and heat stabilizers. However, ecological fears enforced a constraint on the usage of such additive. Consequently, further researches were carried out by Barder resulted in the discovery of a thermoset resin named Crestapol 1234. The latter has the ability to overcome extreme heat temperature degrees above 300°C and has better physiognomies than those available in the market (Bai, 2013) [4].

Chapter 3

Service Life Assessment and Life Cycle Cost Analysis

3.1. Overview

This chapter discusses in-depth the service life of newly planned structures, as well as extending the service life of existing ones. Accordingly, the researcher will present the factors and mechanisms causing the deterioration of reinforced concrete structures, as well as the principles and models behind the Service Life Analysis (SLA). In addition, a comprehensive review of the economical parameters affecting the rehabilitation process utilizing ACMs on the deteriorated structures in order to extend their respective service life. Furthermore, an in-depth review of the Life Cycle Cost Assessment (LCCA) technique used in the economical analysis and feasibility of various rehabilitation methods utilizing ACM's will be presented.

While ACMs possess a great deal of vital characteristics that permit its utilization in numerous applications such as its low weight, outstanding strength and stamina, as well as exceptional ability to resist fatigue, the cost correlated with its use and the degree of life-extension to the structure is questionable. Therefore, both the SLA and LCCA models utilizing ACMs as a rehabilitation/repair material to deteriorated structures will be presented in brief along with the uncertainties aspects that may influence and alter the results and produced data.

3.2. Factors influencing the deterioration of reinforced concrete

Concrete is known to be a brittle material. It gains strength during its life cycle. However, as stated earlier, due to the introduction of steel reinforcement in the past century, concrete became vulnerable to deterioration factors that affect its durability. While the reinforcement served well in terms of reducing the structural elements sizing and quantities, the accumulation of steel rusting within the concrete matrix imposes immense stresses on the built structure. As a result, breakage of concrete became an expected parameter after a certain time during the service life of the structure.

On the other hand, other factors that affect the durability of concrete include carbonation, chloride ingress, moisture transition and susceptibility to various aggressive agents.

3.2.1. Mechanisms causing reinforcement corrosion

According to Nilsson et al. (2016) [122], corrosion of steel reinforcement in concrete occurs whenever the passivity of surface of steel in contact with the concrete is damaged. This can occur whenever the pH level drops in the concrete, which eventually results in carbonation. Similarly, this could also happen when a chloride content in the reinforced concrete reaches the critical or "threshold level". The rapidness of corrosion could vary depending on the properties of the concrete matrix, cover dimension, and the aggressive surrounding environment.

3.2.1.1. Carbonation

Carbonation is a long-term process referred to as the neutralizing process. The latter consists of a chemical reaction between Calcium Hydroxide ($Ca(OH)_2$) and calcium–silicate–hydrate (C–S–H) in the concrete's cement paste hydrates with the availability of Carbon Dioxide (CO_2) that results in Calcium Carbonates ($CaCO_3$) (Chang and Chen, 2006) [123].

$$CO_2 + CaO \rightarrow CaCO_3 \qquad \text{Equation 3-1}$$

3.2.1.2. Chloride Content

According to ACI 318-95 [124], the maximum allowable chloride ion content by weight of cement in reinforced concrete is 0.15 for Sulphate Resisting-Cement (SRC, usually below ground level or in areas in direct contact with soil) and 0.30 for Ordinary Portland-Cement (OPC). On the other hand, unreinforced concrete, such as surface concrete is taken to be 0.60. Beyond these levels, the reinforcement of concrete begins to corrode.

The chlorides accessibility and level in concrete can vary depending on the following factors (Nilsson et al., 2016) [122]:

- The original amount of chlorides available at the time of concrete pouring.
- The ingress amount of chlorides within the transporting agent (such as water) penetrability.
- Ability of chloride bonding into the concrete.

- Cracks availability within the concrete matrix.

3.2.2. Concrete Properties and Reinforcement Corrosion

According to Nilsson et al. (2016) [122], the concrete properties that are correlated with the instigation of reinforcement corrosion are the following:

a) Endurance against the CO_2 dispersion.

b) The level and degree of CaO available during the carbonation process.

c) Transportation and fixation properties of the transporting agent (moisture).

d) Level of chloride threshold and binding ability in the carbonated concrete.

e) Concrete resistance properties towards transporting agents (such as water).

3.3. Service Life Prediction Models

Tuutti (1982) [125] was the pioneer whom first introduced the service life model by analyzing and illustrating the parameters leading to corrosion of steel reinforcement. The research was carried out considering mapping out the diverse mechanisms that regulates the development of corrosion through the estimation of initiation of corrosion period, the time flow rate in which a threshold is reached of infiltrating substances into the concrete that would result in corroding the reinforcements, and the duration of exposure, commonly known as the Propagation Period. These conditions depend greatly on the surrounding environmental factors, such as: relative humidity (RH), temperature (T), composition of the concrete matrix, thickness of cover, porosity of the concrete, degree and level of defects in the produced components of various materials, and the availability of cracks. Correspondingly, the sequence in which steel corrodes in concrete is illustrated in Figure 3.1 below:

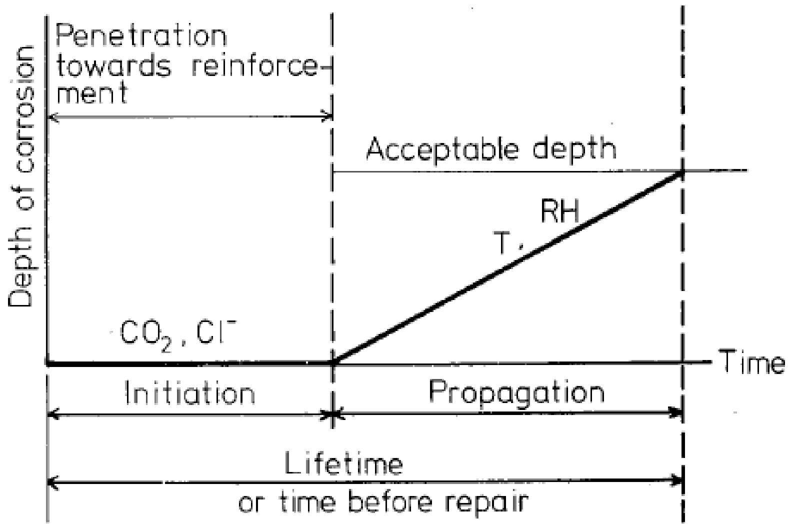


Figure 3.1 – Schematic Sketch of Steel Corrosion Sequence in Concrete.

Source: Tuutti, K. (1982) [125, F19]

Finally, Tuutti (1982) [125] was able to produce a model that is able to predict the service life of reinforced concrete. While the model was a breakthrough in predicting the service life of concrete structures and is supported by laboratory investigations carried, it required further development to attain an enhanced model.

Therefore, an association of ACI's Strategic Development Council (SDC) was established to attain an improved model of service life of reinforced concrete structures. The development of this computer-aided model was a combination of contribution by several parties and industry members, such as Master Builders, Inc. (Brad Violetta and Matt Miltenberger), Grace Construction Products (Timothy Durning and Neal Berke), the Silica Fume Association (Terence Holland), and the University of Toronto (Michael Thomas and Evan Bentz). In addition, other associates participated in the development of the Service Life Modeling incorporated NIST, the National Ready-Mixed Concrete Association (NRMCA), ACI, and the Concrete Corrosion Inhibitors Association (CCIA) (Violetta, 2000) [126]. As a result, a computer-aided prediction model called Life-365 was produced.

According to the consortium, in order to attain the service life prediction model, the following steps must be followed (Bentz et al., 2015 [Life-365 Manual]) [129]:

- Predicting the Initiation Period t_i, which the time required towards the commencement of steel reinforcement corrosion.
- Predicting the time duration of corrosion to a detrimental extent (the propagation period t_p).
- If repair was previously done on the structure, the time in which the first repair is performed is referred to as t_r and equals to $t_i + t_p$.
- Predicting the repair frequency periods required.
- Assessing the life-cycle cost constructed on the original used concrete, additives, and protection expenses and estimating maintenance and repair costs.

3.3.1. Predicting the Initiation Period

The overall service life of reinforced concrete is estimated based on the initiation period, which is the period that is required for the reinforcement to begin corroding adding to it the propagation period (Tuutti, 1982) [125]. In order for steel reinforcement to initiate corrosion, a sufficient amount of chlorides has to infiltrate the concrete cover (x_d) towards the internal reinforcement. The critical threshold of which the chloride concentration can initiate the corrosion after bypassing the cover is referred to as C_t. The approach used in the modelling utilizing Life-365 is based on Fickian diffusion that was originally derived by Adolf Fickian back in 1855 and is based on the environmental exposures on the structure, sealants and additives supplement protection materials embedded in the concrete (such as corrosion inhibitors, CIs) or covering the concrete surface (such as protection membranes), as well as geographical location and concrete cover (Bentz et al., 2015 [Life-365 Manual]; Boddy et al., 1999) [129, 130].

3.3.2. Predicting Chloride Diffusion Ingress

According to Nilsson et al. (2016) [122], The mass balancing equation for predicting the chloride ingress due to diffusion is governed by Fick's 1^{st} and 2^{nd} laws equation:

$$\frac{dC}{dt} = \frac{d}{dx} D_{F1} \frac{dc}{dx} \Leftrightarrow \frac{dC}{dt} = \frac{d}{dx} \frac{D_{F1}}{\frac{dC}{dc}} \frac{dC}{dx} \Leftrightarrow \frac{dC}{dt} = \frac{d}{dx} D_{F2} \frac{dC}{dx} \qquad \text{Equation 3-2}$$

Where C is the total chloride content, dC/dc is the chloride binding capacity, D_{F1} is the diffusion coefficient in Fick's 1st law, where x and t are the depth, and time respectively, and D_{F2} is the diffusion coefficient in Fick's 2nd law. In service life models, both diffusion coefficients are usually used.

Since the chloride diffusion coefficient is correlated to time and temperature, the account for changes in diffusion based on time and temperature are governed by the following equations respectively (Bentz et al., 2015 [Life-365 Manual]; Boddy et al., 1999) [129,130]:

$$D(t) = D_{ref} \cdot \left(\frac{t_{ref}}{t}\right)^{m} \qquad \text{Equation 3-3}$$

Where D(t) = diffusion coefficient at time t, D_{ref} = diffusion coefficient at time t_{ref} (= 28 days in Life-365), and m = diffusion decay index, a constant (Bentz et al., 2015 [Life-365 Manual]; Boddy et al., 1999) [129,130].

$$D(T) = D_{ref} \cdot exp\left[\frac{U}{R} \cdot \left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \qquad \text{Equation 3-4}$$

Where D(T) = diffusion coefficient at time t and temperature T, D_{ref} = diffusion coefficient at time t_{ref} and temperature T_{ref}, U = activation energy of the diffusion process (35000 J/mol), R = gas constant, and T = absolute temperature. The concrete temperature (T) differs as a function of time-dependent based on the chosen geographical location of the modeled structure (Bentz et al., 2015 [Life-365 Manual]; Boddy et al., 1999) [129,130].

3.3.3. Predicting Carbonation Extent

While moisture content and relative humidity surrounding the concrete differs by the season, Nilsson et al. (2016) [122] determine the carbonation models through the penetrability and transport properties of concrete using equation 3-5 as follows:

$$x_{CO_3}(t) = \sqrt{\frac{2D_{CO_2}\, c_{CO_2}}{a}} \cdot \sqrt{t} \qquad \text{Equation 3-5}$$

Where x_{CO_3}= depth of carbonation, D_{CO_2}= diffusion coefficient for CO_2; c_{CO_2}= concentration of CO_2 at the concrete surface, a is the necessitated CO_2 to carbonate a unit volume of concrete, and t is the time (Nilsson et al., 2016) [122].

However, the latter equation does not consider the variation of moisture content and relative humidity levels due to different environmental seasons surrounding the concrete, the equation above requires further investigations to include correction factors that would consider the influence of cracks and resistance against the diffusion of CO_2 (Nilsson et al., 2016) [122].

Since the carbonation is a long-term process and is generally considered in low cover and quality concrete, it can be easily fixed by regular maintenance and decarbonisation of concrete. Thus, Life-365 ignores the extent of carbonation (Bentz et al., 2015 [Life-365 Manual]) [129].

3.3.4. Effects of Cracks on Reinforcement Corrosion

Although service life models generally deal with sound concrete and do not take into account the presence of cracks in structure, it remains a major concern that could influence the service life of concrete structures. The cause of these cracks could be a result of: early-age, thermal loading, shrinkage, or a simple mechanical overloading (Nilsson et al., 2016) [122]. Cracks presence in any structural element is usually not considered favourable. They could stimulate the rapidness of deterioration and evidently the service life of the structure immensely as cracked concrete decreases the initiation corrosion period, and increase the diffusion of aggressive agents (such as chloride ions) that eventually speeds up the corrosion process by granting high penetration conditions. Cracks could be classified into two types, the first being from the quality of workmanship at the time of casting (initial cracking), while the second relates to the service cracks (secondary cracking) that appears due to the frequency of loading and unloading on the structure (Nilsson et al., 2016) [122].

According to Francois and Arliguie (1998) [127], the presence of cracks within the structure allows for a higher rate of harmful and aggressive agents penetration into the concrete matrix. However, the study performed by them determined that the progression of reinforcement corrosion is not mainly affected by the crack width only, but mainly due to the applied loadings and generated tensile stresses on the structure that allows for penetration of aggressive agents. Hence, the presence of cracks affects the service life of the structure in question and shall be treated appropriately.

3.3.5. Uncertainties in Service Life Model

The uncertainties in reinforced concrete service life can be estimated through the uncertainty in the initiation period excluding the propagation period (Tuutti, 1982) [125]. The uncertainties parameters used to predict the probability density function of initiation period of the concrete mixture design affecting the service life model include (Bentz et al., 2015 [Life-365 Manual]) [129]:

a. D28 (%): D28 is the covariance term, which is the initial diffusivity of the concrete predicted at 28 days following the mixing and setting of concrete. It is measured in meters-squared per second (m^2/s). This term varies and deviated in accordance with the hydration and monthly temperatures.
b. m (%): The reduction in diffusivity (diffusion decay index covariance term) or the capability of chlorides to relocate in the concrete matrix in accordance with the hydration levels of concrete as time pass.
c. Cs (%): The maximum surface chloride level in percentage (covariance term).
d. Ct (%): The concentration of chlorides covariance term on the exterior reinforcement steel, which triggers the commencement of corrosion. It is also referred to it as the chloride concentration threshold.
e. Cover (%): The clear cover of concrete covariance term.

3.4. Life Cycle Cost Analysis (LCCA) Principles

Life cycle cost analysis (LCCA) in construction is a well-recognized method that is used to estimate and assess the costs inflicted on a project during its service life through the comparison of various alternatives to attain the most efficient cost in terms of cost, quality, and function of the intended construction (Fuller, 2006) [131]. The life cycle cost analysis presented in the case study utilizes various techniques that would help in decision making of whether repairing and rehabilitation of structures is more cost effective than demolition and reconstruction of the structure in question.

Accordingly, the measures affecting the life-cycle cost assessment and overall cost in comparison with the proposed of a project in the duration of its life span shall include, but not limited to:

3.4.1. Initial Costs (IC)

Initial costs are referred to the land acquisition and entire construction cost taking into consideration the design, procurement, and construction until the handing over of the structure. Since the government grants the land inside the island of Abu Dhabi, the land acquisition price is not considered in the researcher's calculations.

3.4.2. Operation, Repair, Replacement and Maintenance Costs

The costs that are related to the operation/service, repairing of defects and damages, replacement of material/items, and maintenance during the service life of the given structure.

3.4.3. Interest and Inflation Rates

In economics, interest and inflation rates are interconnected, whereas the interest rate is a varied term that rises and decreases in according to the fluctuation in inflation rate, while the inflation rate is the escalation of material prices over time as the currency value decreases due to various factors, such as overprinting of currency, and purchasing power decrement (Kolhatkar and Dutta, 2013) [132].

3.4.4. Discount Rate

Discounting technique is used in evaluating the future value to the current present value by means of a specific percentage rate. While different countries vary in terms of the discount rates, it is usually determined to range from 3% to 7% (Ni, 2017) [133].

3.4.5. Rate of Return (ROI) and Payback Period on Investment

In general, the rate of return on investment utilizes the "Maximization of the ratio of benefits over costs of an investment" concept as identified by Joseph R. Matthews (2011) [134]. Accordingly, the payback period on a specific investment (such as a construction project) shall be maximized to meet a minimum criterion that supersedes the inflation and interest rates, which eventually yields profit on the overall service life of the project. The common ROI usually ranges from $4 - $6 for every dollar spent but may increase depending on the designed and functionality of a project (Matthews, 2011) [134].

3.4.6. Net Present Value (NPV)

The NPV methodology can be illustrated through the difference among the cash inflows and outflows of the present value. The profitability of a specific choice over an alternative choice is determined by the value of the NPV, whereas a positive value yields a profitable choice, while a negative one yields a loss in that option (Investopedia, 2017; Magni, 2005) [135,136].

3.4.7. Sensitivity Analysis (SA)

According to Iloiu et al. (2009) [137], the sensitivity analysis is “an estimate of the effect on achieving project objectives if certain assumptions materialize or not”, additionally, it “is a technique for investigating the impact of changes in project variables on the base-case (most probable outcome scenario)” Correspondingly, SA helps in recognizing the fundamental variables and consequences in alterations to these values that impact various economical parameters such as the cost of a specific development and the adding value streams. Hence, SA helps in decision making of the optimum choice that has the least negative outcomes on the case study.

Costs usually vary in amount and effect on the formation of the decision-making process on the investment from each of the factors mentioned above. Thus, for every alternative, the significant costs affecting throughout the life span of the project shall be taken. Accordingly, costs are structured in accordance to the current amount values, and the LCCA technique predicts their future amount value at the end-life of the structure and escalates discounts them in return to the original commencement date to translate them to the current present values (Fuller, 2006) [131]. The approach in which the most efficient and cost-effective decision is known as cost estimating or value engineering in construction.

Chapter 4

Research Methodology

4.1 Overview

In this chapter, the researcher portrays the methodology and techniques embraced in accomplishing its objective. Accordingly, the research aim and objectives are defined with an in-depth review of the tests and prediction modelling and procedures performed by the adopted report performed by eFORCE team. Furthermore, it offers guide and parameters for comparing the retrieved data performed by eFORCE team with the executed models and data gained performed by the researcher for the case study.

4.2 Research Approach

The literature review presented the importance of introduction to more advanced building materials for a more sustainable construction as well reduction in maintenance and rehabilitation costs of built structures. Accordingly, the research approach is to quantify the data collected numerically from the visual inspection and tests that were previously performed and assess the existing case study in terms of service-life and life cycle cost. The model that is performed by the researcher shall be built on the extracted results from the previous service-life model done by eFORCE team. In addition, the research will perform the life cycle assessment of the structure to compare the viability of service-life modeling produced in utilizing ACM's in rehabilitation of various structures in the GCC region.

The case presented in this study focuses on the service life from the time of construction till the end life of the structure and comparing it with the life cycle cost feasibility models of utilizing micro-concrete advanced composite materials in rehabilitation of these deteriorated structures. The data collected are from eForce Inspection Consultancies Report (2013) [140] previously performed on 30th January 2013 in close co-ordination with various well-known and reputable manufacturers of micro-concrete ACMs for rehabilitation of deteriorated structures. The data and information gained included detailed data sheets of materials procured in various projects. Correspondingly, the study that is performed by the researcher identifies the different elements affecting the deterioration of the structure including time-dependent factors affecting the rehabilitation of the buildings in gulf region. Equally, by comparing the service life model previously performed by eFORCE team along with service life model and life cycle cost assessment performed by the researcher in application on the case study, the results are used to defy the suitability of utilizing rehabilitation advanced composites in the case study, which defines the purpose of this research.

4.3 Research Strategy

As stated earlier, the aim of this study is to numerically examine the feasibility of applying ACMs in rehabilitation of deteriorated structures in the gulf region through the data and models produced. The analysis will be carried out by determining the overall service life prolongation period if utilized in the deteriorated structure presented in the case study of the eight-storey building constructed in Abu Dhabi back in 1976.

In addition, the analysis will extend to include the life cycle cost of the structure during its original service life, as well as after applying the rehabilitation measures. The results of the modeling performed by the researcher will be compared to the outcomes of the report presented by eFORCE team. Consequently, the recommendations will be given based on the realistic data of both service life models performed by eFORCE team and the researcher, as well as the life cycle cost assessment performed by the researcher.

The strategy embraced in this research to attain the service life model consists of the following:

- Collecting data that are necessary in analyzing the structure through Visual Inspection.
- Collecting data from the performed coring tests on the columns and foundation of the structure to determine the concrete compressive strength.
- Attaining the current condition and dimension of the concrete cover to the reinforcement through a digital cover meter for various structural elements.

- Measuring the depth of Carbonation on freshly broken surfaces of the concrete.
- Conduct chloride test on dust samples.
- Conduct the half-cell potential tests to provide the probability of steel corrosion.
- Determine the concrete quality utilizing the Ultrasonic Pulse Velocity test.
- Conduct the electrical resistivity test of concrete surface to acquire the rate of steel corrosion.
- Perform a service life model by the researcher and compare it with the previous model performed by eFORCE team.

The strategy embraced in this research to attain the life cycle cost assessment consists of the following:

- Collecting data concerning the initial cost, operation, repair, and replacement and maintenance costs of the existing structure.
- Collecting data concerning the interest rate, discount rate, and inflation rate of the building materials in the market.
- Calculating the net present value, rate of return, rate of return, payback period, and resale value of the structure.
- Evaluate the risks and uncertainties associated with the economical life cycle cost assessment.

The results of the comparisons are used to draw a conclusion on the viability of the service life model performed. In addition, the life cycle cost assessment shall present the consistency and feasibility of the proposed rehabilitation technique proposed by eFORCE in performing the repair of the deteriorated structure in the case study.

4.4 Data Collection

The data collected in this study is based on the report presented by eFORCE team dated 30th January 2013 as well as plenty of meetings and emails with various consultants and manufacturers of rehabilitation micro-concrete advanced composite materials. Accordingly, the data collected were from the following sources:

- The structural integrity investigation report performed by Dr. Ashraf Biddah from eFORCE team.
- Building structural history from Eng. Mohammad Subeh from National Engineering Bureau.
- Structural rehabilitation methods and feasibility studies performed by Golden Planners Engineering Consultatns L.L.C.
- Demolition and construction costs feasibility studies performed by Golden Planners Engineering Consultants L.L.C, Abu Dhabi Commercial Engineering (ADCE), and Kiwan Demolishing Contracting Company.
- Building materials costs from Statistics Center Abu Dhabi (SCAD)
- Email communications, as well as meetings with Eng. Mahmoud Atteya, Target Marketing Manager and Aun Jafar from Sika GCC.
- Email communications, as well as meetings with Eng. Moheb Malik and Ashraf Raouf from BASF Middle East.
- Email communications, as well as meetings with Eng. Ashraf Hasania from Cortec Industries.

4.5 Applied Softwares

The data that were attained are analyzed utilizing Life-365 program as well as Microsoft Excel. The service life models were prepared using Life-365 is in accordance with the data from the American Concrete Institute and British Standards. As stated earlier in section 3.3, life-365 program was produced as a result of the establishment of an association from ACI's Strategic Development Council (SDC) to attain an improved model of service life of reinforced concrete structures. The development of this computer-aided model was a combination of contribution by several parties and industry members, such as Master Builders, Inc. (Brad Violetta and Matt Miltenberger), Grace Construction Products (Timothy Durning and Neal Berke), the Silica Fume Association (Terence Holland), and the University of Toronto (Michael Thomas and Evan Bentz). In addition, other associates participated in the development of the Service Life Modeling incorporated NIST, the National Ready-Mixed Concrete Association (NRMCA), ACI, and the Concrete Corrosion Inhibitors Association (CCIA) (Violetta, 2000) [126]. As a result, a computer-aided prediction model called Life-365 was produced.

Meanwhile, the Life Cycle Cost Analysis prepared by the researcher utilizes parameters such as the inflation and discount rates, and construction costs of various building materials. Based on these data, the researcher presented the Life-Cycle Cost graphs, Constant and Cumulative Costs, Current Costs, and Cumulative Current Costs timelines, and the Sensitivity Analysis to the previous stated parameters.

Chapter 5

Results and Discussions

5.1 Overview

This chapter aims to present the results of the service life modeling for the case study performed by both, the researcher and eFORCE team and compare between them. In addition, it shall present the results of the life cycle cost assessment of the case study performed by the researcher to validate the feasibility of rehabilitation deteriorated concrete structures using micro-concrete advanced composite materials. Accordingly, the researcher will perform an analysis and modeling comparison on a submitted structural integrity testing report by eFORCE (Center for Engineering Studies & Consultancy Services) for repairing of a deteriorated concrete building in the city of Abu Dhabi in the United Arab Emirates for Plot No. C-74 located in East 13 of the city that consists of Ground + 8 Typical + Roof floors. The study will undertake the efficiency of the utilization of micro-concrete in repairing the structure against demolition and reconstruction of the deteriorated structure. Furthermore, the researcher will perform an economical analysis through a life cycle cost assessment of both options to determine the most economical and feasible choice.

The analysis performed will guide to a resolution to difficulties faced in terms of adopting micro-concrete advanced composites, how well would micro-concrete composites perform in real life applications, prolongation of service life and economical value and feasibility of utilizing micro-concrete composites compared to other advanced composites in the rehabilitation of deteriorated structures, downsides of using micro-concrete, and the various factors affecting efficiency and reliability in utilizing micro-concrete in deteriorated structures.

It is essential to note that both eFORCE team and the researcher perform the service life models only on columns due to the lack of sufficient data on the beams, slabs and pile cap presented in eForce Inspection Consultancies Report (2013) [140].

5.2 Case Study

Examining the structural system of the buildings, as well as eForce Inspection Consultancies Report (2013) [140], we note that the structure comprises of solid and hordy slabs on beams and columns, while the foundation system is based on pile caps over piles. The building under consideration can be seen in Figure 5.1 below:

Figure 5.1 – Structure Undergoing Investigation.

Source: eForce Inspection Consultancies Report (2013) [140, F20]

As stated earlier, assessing the validity of utilizing ACM's in repairing and rehabilitation of deteriorated structures in the gulf region in accordance with ACI standards necessitate performing the analysis based on the actual deteriorated building located in the region. Thus, the study will undertake the existing building consisting of ground floor plus eight stories plus roof floors where a previous service life study was performed by eFORCE team and compare it with the results performed by the researcher. The investigation performed utilizes Life-365 software to determine the service-life analysis of the structure with and without repair based on the tests performed on the building. In addition, a Life Cycle Cost Analysis utilizing the LCA technique on the deteriorated elements in the structure to evaluate the cost to value parameter of utilizing micro-concrete ACMs in the repair of the structure against the extended service-life analysis of the structure. The results will be analyzed and discussed in terms of feasibility and efficiency accordingly.

The building considered in the case study is located in Tourist Club in Abu Dhabi, United Arab Emirates. The plan of the building is a rectangular shape with a central two cores, one for the lifts and the other for the staircase. The deterioration is mainly studied on sample from columns in various floors as well as a sample from the pile cap.

5.3 Test Results Performed by eFORCE Team

The test results performed by eFORCE team can be summarized by:

5.3.1 The Visual Inspection of the Structure

The visual inspection of the building revealed an immense extent of cracking and delamination in the concrete due to steel corrosion. The corrosion of various steel reinforcements in diverse structural elements is visible. Accordingly, the corrosion can be seen in structural columns, as well as slabs revealing signs of a previous severe leakage. As a result, delamination and breakage of concrete surface is observed as illustrated in Figure 5.2 below:

Figure 5.2 – Corrosion of Steel Reinforcement in Structural Members (Columns and Slabs)

Source: eForce Inspection Consultancies Report (2013) [140, F20]

5.3.2 Coring Tests Performed by eFORCE team

The coring is done through sampling of five different columns in various locations and one pile cap was performed utilizing the coring of the columns (horizontally) and the pile-cap (vertically) in the building are shown in Figure 5.3 below:

Figure 5.3 – Coring Samples from Columns and Pile Cap

Source: eForce Inspection Consultancies Report (2013) [140, F20]

The cores were denoted as C1 to C6. C1 core sample is taken from a ground floor column that is located in the exterior façade of the building and directly subjected to environmental conditions, while C2, and C3 are for internal columns located on the ground floor. C4 and C5 are the core samples taken from the first and fourth floor columns respectively, while C6 is the core sample taken from the underground pile-cap. The corresponding core tests performed to cores C1 to C6 are denoted by T1 to T6 in the following tables. It is essential to note that all coring works were performed in the horizontal direction except for the pile-cap core, which the direction of coring taken is vertical. The compressive strength tests were carried out according to BS 1881: Part 120-1983. The results are presented in Table 5-1 below:

Core No.	C1	C2	C3	C4	C5	C6
Advised direction of coring	Horizontal	Horizontal	Horizontal	Horizontal	Horizontal	Vertical
Core length (mm)	104	104	100	103	102	103
Length / diameter ratio, λ	1.41	1.41	1.35	1.39	1.38	1.39
As received bulk density (kg/m^3)	2270	2220	2330	2270	2170	2270
Maximum Failure load (kN)	49	56	57	61	56	52
Compressive Strength (N/mm^2)	11.4	13.0	13.2	14.2	13.0	12.1
Mode of failure	Normal	Normal	Normal	Normal	Normal	Normal
Correction factor due to (l/d ratio)	1.130	1.130	1.116	1.127	1.123	1.037
Correction factor due to reinforcement	1.000	1.000	1.000	1.000	1.000	1.000

Estimated in-situ cube compressive strength (N/mm^2)	12.9	14.7	14.8	16.0	14.6	12.5

Table 5-1 - Concrete Compressive Strength from the Cores

Source: eForce Inspection Consultancies Report (2013) [140]

5.3.3 Cover Meter (CC) Tests Performed by eFORCE Team

Figure 5.4 - eFORCE Team Measuring the CC and Identifying the Steel Bars Locations

Source: eForce Inspection Consultancies Report (2013) [140, F20]

The results of the cover assessment performed on the structure utilizing an electromagnetic cover meter (shown in Figure 5.4 above) are summarized in Table 5-2 below:

Location No.	Description	Min. Reading (mm)	Max. Reading (mm)	Avg. Reading (mm)
T1	Ground floor column (exterior)	9	14	11.5
T2	Ground floor column (interior)	27	32	29.5
T3	Ground floor column (interior)	21	27	24
T4	First floor column	10	15	12.5
T5	Fourth floor column	32	37	34.5
Average		**19.8**	**25**	**22.4**

Table 5-2 - Cover Meter Survey Results.

Source: eForce Inspection Consultancies Report (2013) [140]

5.3.4 Depth of Carbonation Tests Performed by eFORCE Team

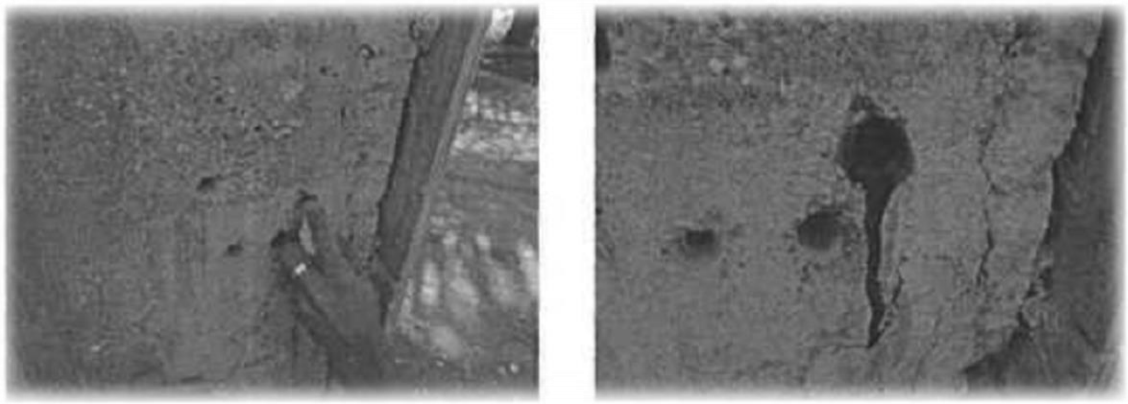


Figure 5.5 - Utilizing 1% Phenolphthalein in Diluted Ethyl Alcohol

Source: eForce Inspection Consultancies Report (2013) [140, F20]

The carbonation test performed on the structure utilized an indicating solution of 1% phenolphthalein in diluted ethyl alcohol as seen in Figure 5.5. When applied, the indicator changes its color to purple-pink when reaches the sound un-carbonated concrete. The results of the test are presented in Table 5-3 below:

Location No.	Description	Carbonation (mm)	Average cover (mm)	Protected or not Protected
T1	Ground floor column (exterior)	16	11.5	No
T2	Ground floor column (interior)	30	29.5	No
T3	Ground floor column (interior)	22	24	Yes
T4	First floor column	16	12.5	No
T5	Fourth floor column	26	34.5	Yes
Average		**22**	**22.4**	**Yes**

Table 5-3 - Carbonation Results

Source: eForce Inspection Consultancies Report (2013) [140]

5.3.5 Chloride Test Performed by eFORCE Team

Figure 5.6 - Dust Sampling

Source: eForce Inspection Consultancies Report (2013) [140, F20]

In the 8-storey building under consideration, the dust samples were gathered from columns as well as the pile cap as seen in Figure 5.6 above and are tested utilizing the Sherwood Model 926 device. Furthermore, the results data are presented in Table 5-4 below:

Test No.	Location	Depth (mm)	Chlorides Ion Content Percentage by Weight of	
			Concrete	Cement
T1	Ground floor column (exterior)	0 - 25	0.0115	0.0690
		25 - 50	0.0192	0.1152
		50 -75	0.0326	0.1956
T2	Ground floor column (interior)	0 - 25	0.0326	0.1956
		25 - 50	0.0173	0.1038
		50 -75	0.0384	0.2304
T3	Ground floor column (interior)	0 - 25	0.0211	0.1266
		25 - 50	0.0134	0.0804
		50 -75	0.001	0.0066
T4	First floor column	0 - 25	0.0173	0.1038
		25 - 50	0.0384	0.2304
		50 -75	0.0595	0.3570
T5	Fourth floor column	0 - 25	0.0211	0.1266
		25 - 50	0.0288	0.1728
		50 -75	0.0902	0.5412
T6	Pile cap	0 - 25	0.0250	0.1500
		25 - 50	0.0192	0.1152
		50 -75	0.0173	0.1038

Table 5-4 - Samples of Chloride Content

Source: eForce Inspection Consultancies Report (2013) [140]

5.3.6 Half Cell Potential Test Performed by eFORCE Team

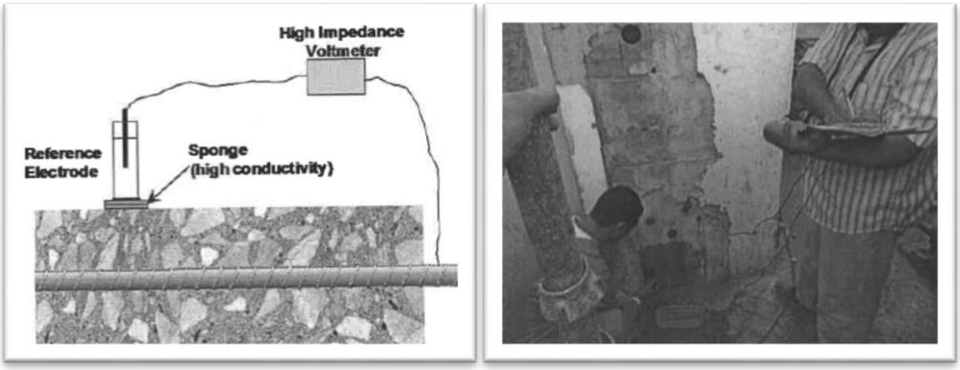


Table 5-5 - Half-Cell Potential Measurement Test as Executed

Source: eForce Inspection Consultancies Report (2013) [140, F20]

Half-cell potential test is a recognized method of testing the likelihood of steel reinforcement corrosion in concrete. The electro half-potential test was performed utilizing the Canin System for measuring the potential apparatus on the concrete surface of the structure in question at two different (2) locations. The assessment involved performing grid readings spaced at 100mm at the selected locations. The results are presented in Table 5-6 below:

Half-Cell Potential Measurements							
Test No.	Location	Reading Values (mV)		% Measurements			
		Min.	Max.	< - 200 mV	-200 to -350 mV	> -350 mV	No. of Readings
T1	Ground floor column (Exterior)	-241	-220	0	100	0	9
T4	First floor column	-68	-24	100	0	0	9
Significance as per ASTM C876-91				More than 90% Probability of no corrosion	Corrosion is Uncertain	More than 90% Probability of corrosion	-

Table 5-6 - Half-Cell Potential Results

Source: eForce Inspection Consultancies Report (2013) [140]

5.3.7 Ultrasonic Pulse Velocity Test Performed by eFORCE Team

In order to determine the quality and soundness of concrete, the Ultrasonic Pulse Velocity Test was used as illustrated in Figure 5.7 below:

Figure 5.7 - During measuring the Ultrasonic Pulse Velocity

Source: eForce Inspection Consultancies Report (2013) [140, F20]

The velocity of the transmission determines the quality of the concrete, whereas a velocity of 3500 m/s and above is considered an indication for good to excellent concrete quality. Table 5-7 below outline the principles in evaluating the quality of concrete:

No.	Pulse Velocity in core probing (m/sec)	Concrete Quality Grading
1	Above 4500	Excellent
2	3500 to 4500	Good
3	3000 to 3500	Medium
4	2000 to 3000	Poor
5	Less than 2000	Very poor

Table 5-7 - Velocity Criterion for Concrete Quality Grading

Source: eForce Inspection Consultancies Report (2013) [140]

Table 5-8 below presents the test results attained:

No.	Description	Ultrasonic pulse velocity (m/sec.)
T1	Ground floor column (exterior)	1368

T2	Ground floor column (interior)	1851
T3	Ground floor column (interior)	2054
T4	First floor column	1435
T5	Fourth floor column	347

Table 5-8 - Ultrasonic Pulse Velocity Test Results

Source: eForce Inspection Consultancies Report (2013) [140]

5.3.8 Elect. Resistivity Test of Conc. Surface as Performed by eFORCE Team

Figure 5.8 - The Concrete Resistivity Meter

Source: eForce Inspection Consultancies Report (2013) [140, F20]

In the structure in question, the surface resistivity meter (SR) utilized in the assessment of the building is shown in Figure 5.8 above. The two outer probes produce the electrical current and the potential difference is measured through the other two inner probes. The application method is illustrated in Figure 5.9 below:

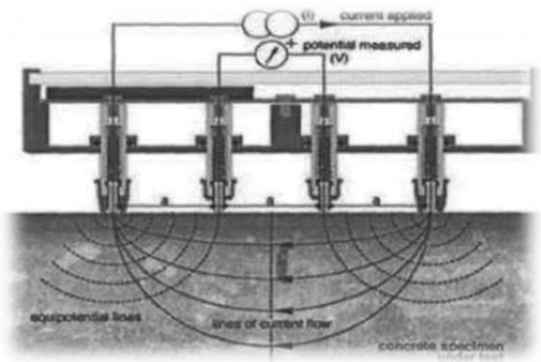


Figure 5.9 - Surface Resistivity Meter

Source: eForce Inspection Consultancies Report (2013) [140, F20]

The resistivity calculations may vary due to the distance between the probes, while the resistivity of concrete readings can be used to ascertain the corrosion probability of the embedded reinforcements. The resistivity unit is measured in terms of [kΩcm] and the likelihood of corrosion is defined in Table 5-9 below:

No.	Concrete resistivity	Interpretation on Corrosion
1	p ≥ 100 kΩcm	Corrosion is unlikely – Low corrosion rate
2	p = 50 to 100 kΩcm	Risk of corrosion is low -Low to moderate corrosion rate
3	p = 10 to 50 kΩcm	Risk of corrosion is moderate - High corrosion rate
4	p ≤ 10 kΩcm	Risk of corrosion is high - Very high corrosion rate

Table 5-9 - Likelihood of corrosion as function of the concrete resistivity

Source: eForce Inspection Consultancies Report (2013) [140]

The assessment performed on the structure are shown in Figure 5.11 and the results are summarized in Table 5-10 below:

Figure 5.10 - eFORCE Team Performing the Concrete Resistivity Test

Source: eForce Inspection Consultancies Report (2013) [140, F20]

Location No.	Description	Resistivity (kΩcm)
Tl	Ground floor column (exterior)	11.9
T2	Ground floor column (interior)	415
T3	Ground floor column (interior)	685
T4	First floor column	48.1
T5	Fourth floor column	60

Table 5-10 - Results of Concrete Resistivity

Source: eForce Inspection Consultancies Report (2013) [140]

5.4 Summary of Service Life Model Performed by eFORCE Team

Based on the lab results, the analysis of the service life of concrete was carried out by eFORCE team utilizing Life-365 software. In the analysis carried out by the team, the assumptions were made that no silica fumes, corrosion inhibitors (CIs) or other additives were added to the original concrete upon construction. On the other hand, the inflation rate economical factor was taken as 1.80% for various construction elements. eFORCE team modeled the structure on Life-365 which presented their values as per the reported values in their report.

It is essential to note that both eFORCE team and the researcher perform the service life models only on columns due to the lack of sufficient data on the beams, slabs and pile cap presented in eForce Inspection Consultancies Report (2013) [140].

5.4.1 The Structure's Service Life Analysis if No Repair is Performed

As reported in Source: eForce Inspection Consultancies Report (2013) [140], the model in case no repair is done on the structure presented the actual values in outer dimensions and clear cover gained in the report as 200 mm and 21 mm respectively. It is predicting a service life of 38.3 years. Accordingly, the model in Figure ED-7 in Appendix B anticipated the initial spalling of concrete to arise after 38.3 years, while the initiation of considerable corrosion of reinforcement is expected to occur after 32.3 years.

Since the building is constructed 37 years ago as of January 2013, then the expected service life in the first model (Figure ED-7) is 38.3 – 37 = 1.3 years. Furthermore, the model presented that the corrosion of reinforcement began earlier than anticipated by 32.3 – 37 = -4.7 years. Accordingly, in case no repair is done, the life expectancy of the building as per eFORCE team can range from 1 ± 1 year(s).

5.4.2 The Structure's Service Life Analysis if Repair is Performed

As reported in Source: eForce Inspection Consultancies Report (2013) [140], in case repair is done, micro-concrete is embedded into the surface and is attached with the chipped concrete. Hence, the years to build to the maximum chloride concentration is extended by 10 years and is assumed to be 47 years instead of 37 years.

The service life results of the model performed by eFORCE team, if repair is performed on the structure, are shown in Figure ED-4 in Appendix B. Accordingly, the initiation of considerable corrosion to the steel reinforcement is predicted to happen after 40.7 years and spalling of concrete after 46.7 years from the construction date of the building. Since the building is 37 years old as of January 2013, the extended service life of the repaired structure is expected to be 46.7 – 37 = 9.7 years with significant corrosion commencing after 40.7 – 37 = 3.7 years.

5.4.3 Proposed Repair by eFORCE Team

eFORCE team proposed the repair of deteriorated slabs where signs of concrete damage and extensive reinforcement corrosion by demolishing and recasting of slabs. On the other hand, moderate signs of damage and reinforcement corrosion slabs can be repaired utilizing shotcrete micro-concrete. Similarly, columns repair exhibiting signs of delamination/damage and reinforcement corrosion can be repaired utilizing patching repair or micro-concrete depending on the damage degree. In addition, the team proposed to use advanced composite materials utilizing micro-concrete on all concrete walls and columns to protect the structural elements from rising carbonation degree and chloride concentration levels in the future. Furthermore, during repair, temporary supports shall be provided for the structural elements to sustain the structural integrity of the building.

5.5 Service Life Model Performed by the Researcher

In the analysis carried out by the researcher, the assumptions were made similar to that of eForce Inspection Consultancies Report (2013) [140] confirming that no silica fumes, corrosion inhibitors (CIs) or other additives were added to the original concrete upon construction. Additionally, the inflation rate and discount rate economical factors were taken as 2% and 3% respectively for various construction elements in accordance with the United Arab Emirates inflation rate outlined in

Trading Economics (2017) [138].

It is essential to note that both eFORCE team and the researcher perform the service life models only on columns due to the lack of sufficient data on the beams, slabs and pile cap presented in eForce Inspection Consultancies Report (2013) [140].

5.5.1 Integrated Data in the Researcher's Service Life Model

The project data integrated within the model are illustrated in Figure 5.11 below:

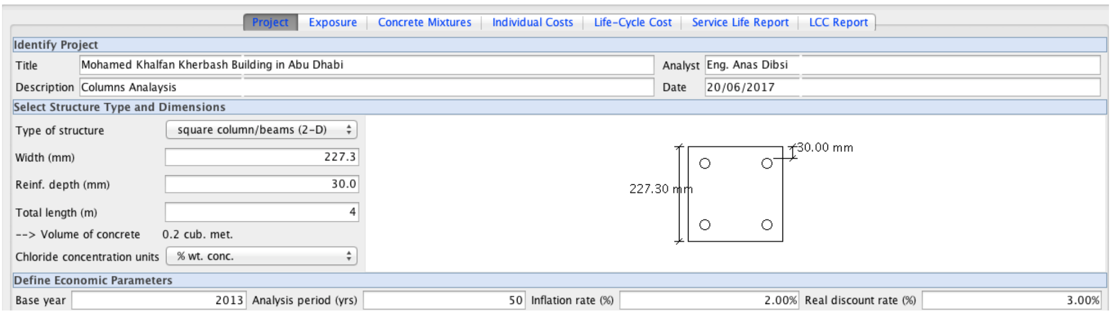


Figure 5.11 – Data Implemented in the Researcher's Model

Since the tests were only performed on five columns and one pile cap by eFORCE team, the analysis performed by the researcher is carried on these elements only. Accordingly, the implemented data in the researcher's model for the columns elements were as follows:

Element: Column	Value
Width	227.3 mm
Reinforcement Depth (Cover)	30.0 mm
Total Length of Element	4.0 m
Chloride Concentration	% Weight of Concrete
Base Year	2013
Analysis Period	50 Years
Inflation Rate	2.00%
Discount Rate	3.00%

Table 5-11 – Implemented Data into the Researcher's Model

While the original values of columns width is equal to 200 mm and average cover is

22.4 mm as per Table 5-2 and Table 5-3, Life-365 does not permit the usage of width value less than 227.3 mm and cover value of less than 30.0 mm. The chloride concentration on the other hand is used as the percentage weight of concrete in accordance with the software requirements.

Meanwhile, the predicted service life model is compared with the original service life design of the structure for a period of 50 years, while the inflation and discount rates are assumed to be 2.00% and 3.00% respectively (Trading Economics, 2017) [138].

The exposure data values integrated within the model are illustrated in Figure 5.12 below:

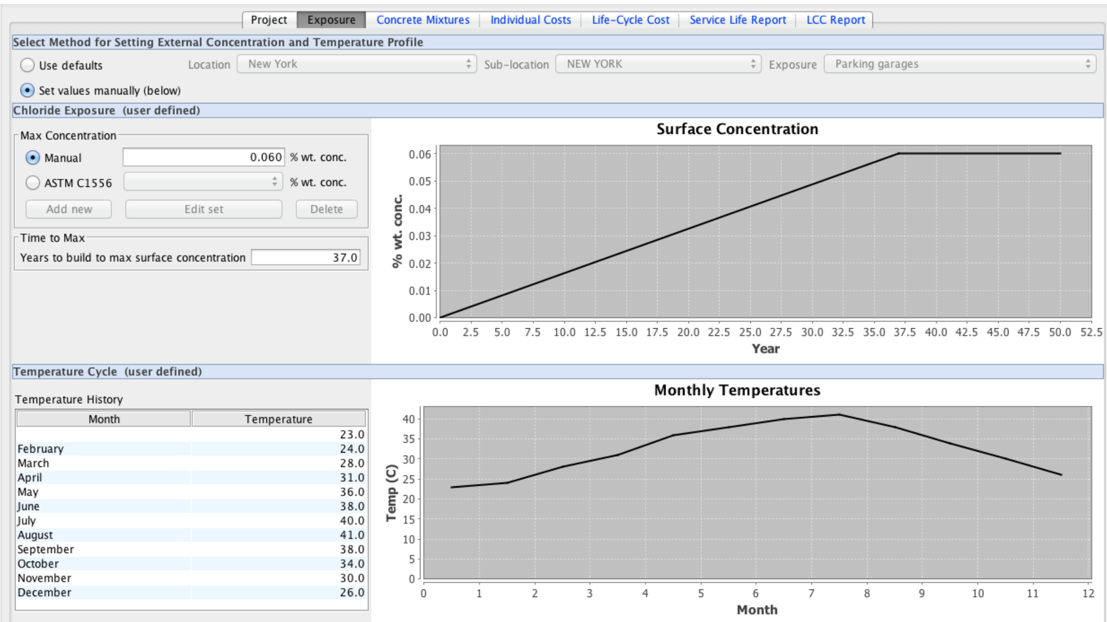


Figure 5.12 – Exposure Data in the Researcher's Model

As stated earlier, in accordance to ACI 318-95 [124], the maximum allowable chloride ion content by weight of cement in reinforced concrete is 0.15 for Sulphate Resisting-Cement (SRC, usually below ground level or in areas in direct contact with soil) and 0.30 for Ordinary Portland-Cement (OPC). On the other hand, unreinforced concrete, such as surface concrete is taken to be 0.60. Correspondingly, as per Table 5-4, the first and fourth floors columns' are higher than the acceptable limits stated earlier with values of chloride content Cl^- by weight of cement are 0.3570% and 0.5412% respectively. Meanwhile, the threshold of chloride concentration values varies nevertheless is usually in the range of 0.05 to 0.1% by weight of concrete. Since the chloride content by weight of concrete is in range from 0.01% to 0.09% for T1 to T6 in Table 5-4, it is assumed in the model that the chloride content is equal to 0.06% (ACI 318-95) [124].

On the other hand, the assumptions made regarding the original reinforced concrete that neither inhibitor additive nor any membrane barrier is contained in the original concrete. Additionally, the assumed used steel reinforcement in the concrete is black steel with a maximum rebar percentage value of 4% by volume of concrete.

On the other hand, the monthly temperatures are determined from World Weather Online (2017) [144] and Weather Spark (2017) [145]. The model analysis performed by the researcher took into consideration the environmental conditions surrounding the building in modeling the service life of the structure prior to performing analysis. In Abu Dhabi, where the building is located, the average temperature is illustrated in Figure 5.13 below:

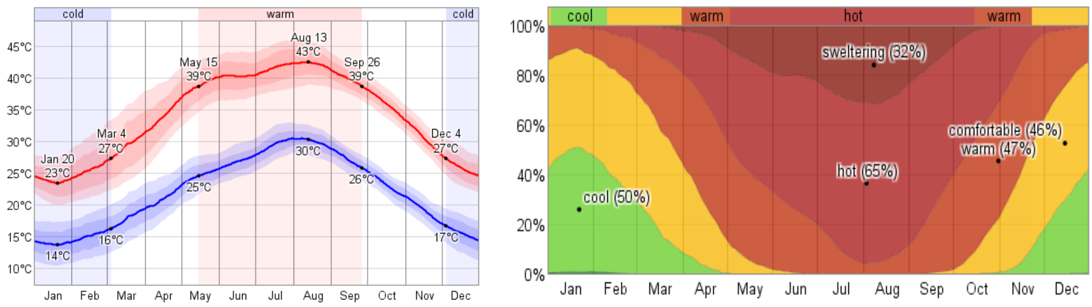


Figure 5.13 - Daily High and Low Temperatures and Fraction of Various Temperature Bands

Source: Weather Spark (2017) [145, F21]

The average monthly temperatures taken into the model are illustrated in Table 5-12 below:

Month	Temperature
January	23.0
February	24.0
March	28.0
April	31.0
May	36.0
June	38.0
July	40.0
August	41.0

September	38.0
October	34.0
November	30.0
December	26.0

Table 5-12 – Average Monthly Temperature in Abu Dhabi

Source: Weather Spark (2017) [145]

Whereas the precipitation and relative humidity are quite high as illustrated in Figure 5.14 below:

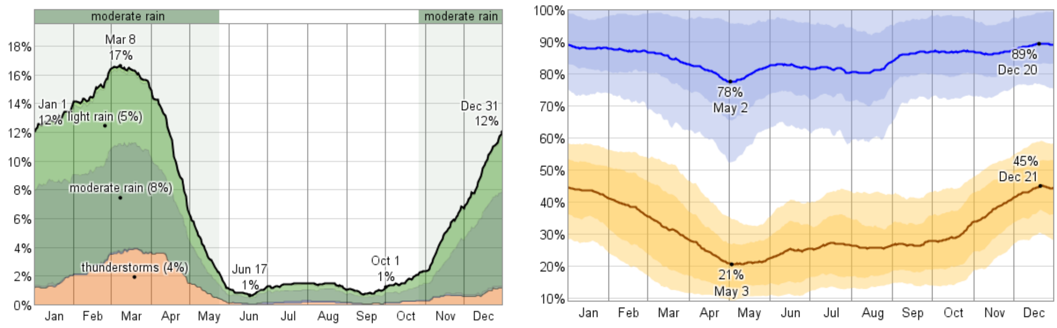


Figure 5.14 - Probability of Precipitation at Some Point in the Day
& The High and Low Relative Humidity is Demonstrated in the Blue and Brown Colors Respectively

Source: Weather Spark (2017) [145, F21]

5.5.2 Service Life Analysis by the Researcher if No Repair is Performed

The model in Figure 5.15 below anticipated the initial spalling of concrete to arise after 40.7 years, while the initiation of considerable corrosion of reinforcement is expected to occur after 34.7 years.

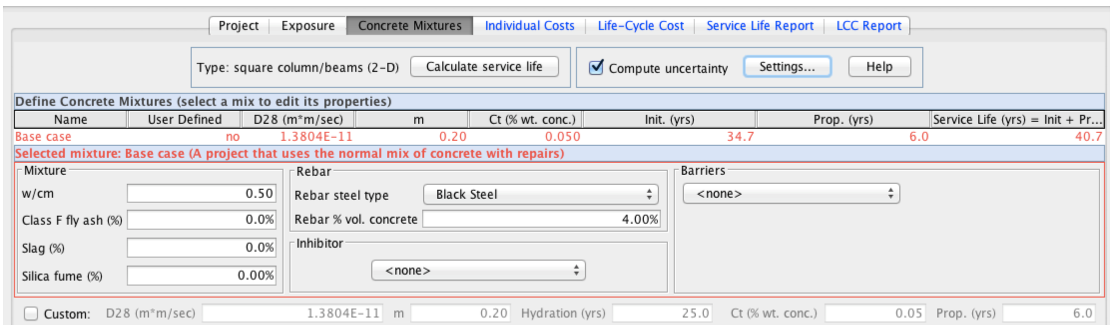


Figure 5.15 – Initiation of Corrosion and Service Life (yrs)

Since the building is constructed 37 years ago as of January 2013, then the expected service life in the researcher model (Figure 5.15) is found to be 40.7 – 37 = 3.7 years.

Meanwhile, the corrosion of reinforcement began earlier than anticipated by 34.7 – 37 = -2.3 years. The latter results can be considered reasonable as the concrete quality is very poor, carbonation of concrete exceeds the cover dimensions, and the high chloride content identified during the tests within the structural columns.

The service life model showing the initiation and propagation periods (IP and PP respectively) of the analyzed structure is illustrated in Figure 5.16 below:

Figure 5.16 – Service Life of the Struc. Illustrating the IP and PP

The concrete cross-section presenting the chloride concentration build-up and saturation degree as a percentage of concrete's weight up to the end of its initiation period is illustrated in Figure 5.17 below:

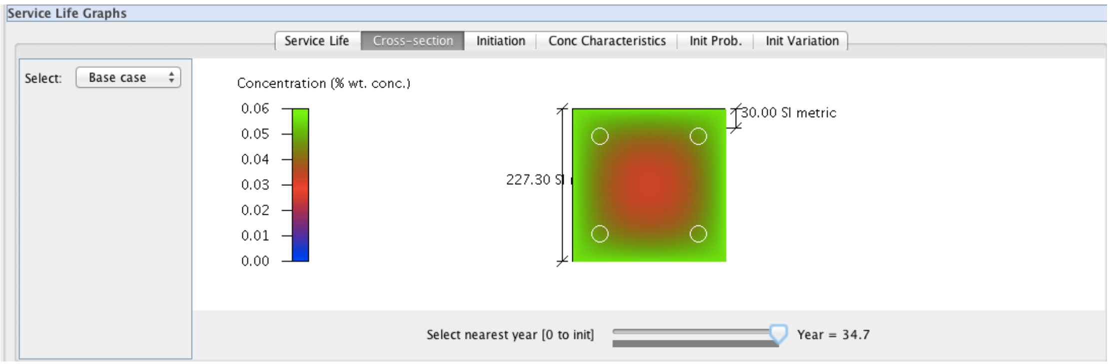


Figure 5.17 – The Chloride Conc. of the Reinforced Concrete Column at IP

The concentration of chlorides (on the vertical axis) at each depth of the analysed columns at the time of initiation as well as the level of chlorides variations at the reinforcing steel (on the vertical axis) at each point in time up to the time of initiation respectively are illustrated in Figure 5.18 below:

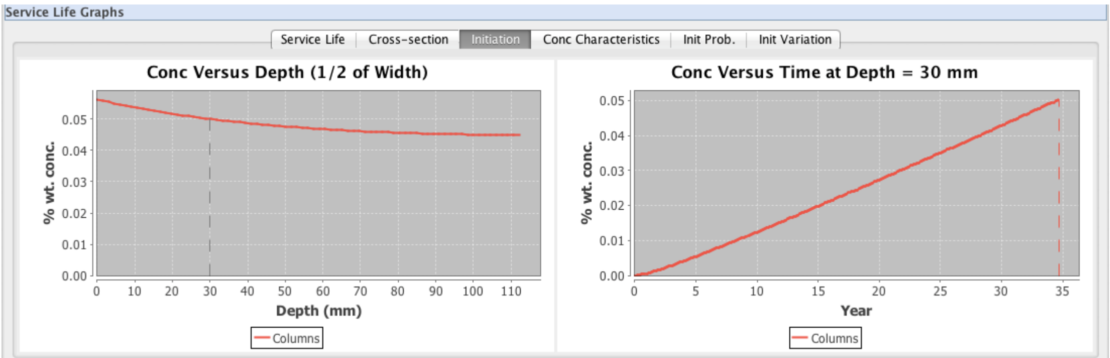


Figure 5.18 – Conc. of Chlorides at Each Depth of the Structure
& the Level of Chlorides at the Reinforcing Steel with Time Respectively

On the other hand, the diffusivity of the concrete and the change in chloride concentration on the surface of the concrete structure over time respectively are illustrated in Figure 5.19 below:

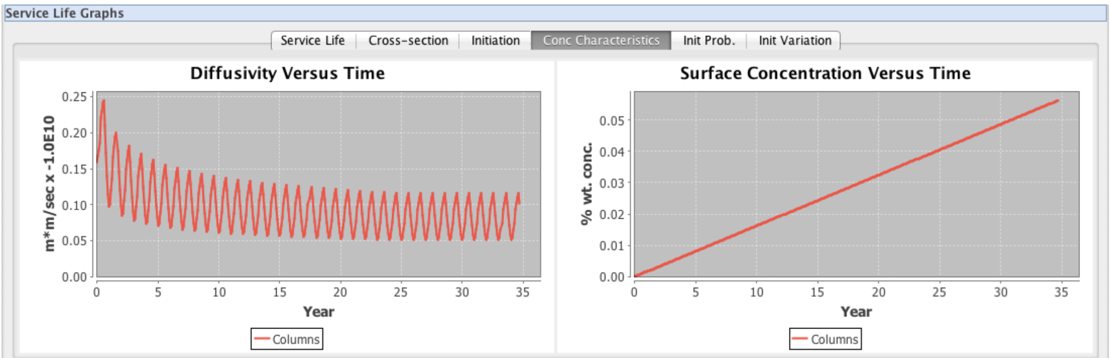


Figure 5.19 – The Diffusivity of the Concrete and the Change in Chloride Conc.
At the Concrete Surface Over Time Respectively

The reason behind the oscillation in Figure 5.19 is due to the diverse temperatures course during the year. Meanwhile, the uncertainty computations outcomes expose the probability density functions of the service life and the cumulative density functions are illustrated in Figure 5.20 below:

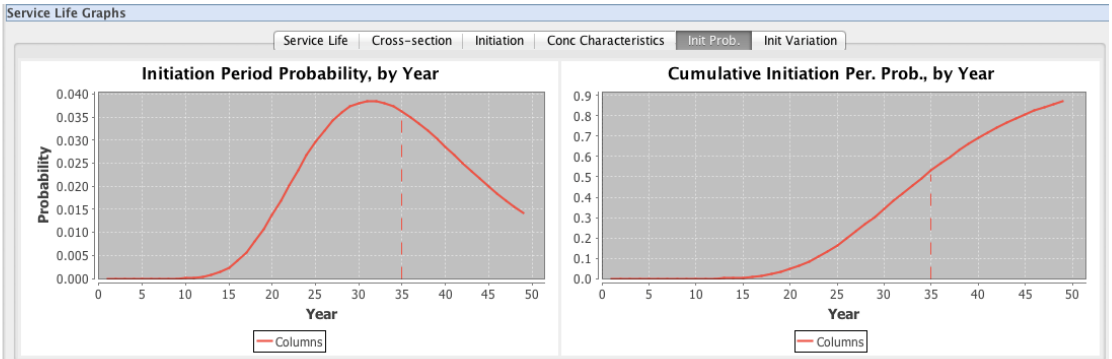


Figure 5.20 – Uncertainty Graphs
illustrating the Initiation Period Probability (by Year) and the Cumulative Initiation Period Probability (by Year)

The model illustrated in Figure 5.21 below considered values of outer dimensions and clear cover as 227 mm and 30 mm respectively. It is predicting a service life with a value of 40.7 years.

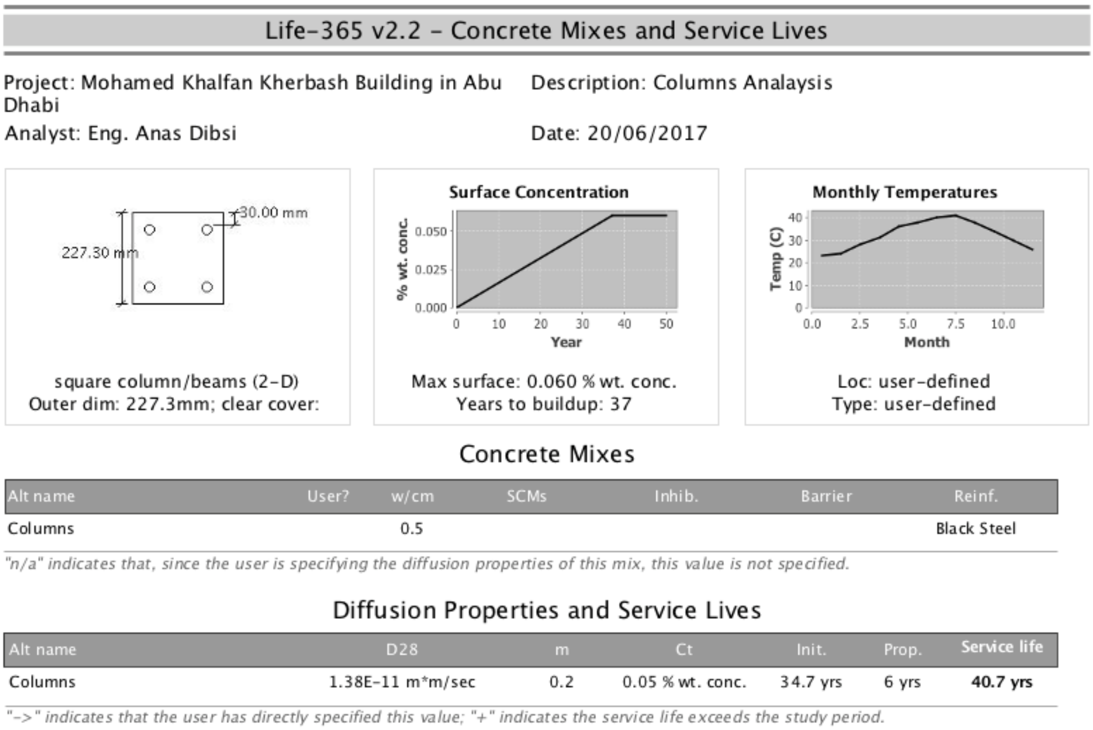


Figure 5.21 – Service Life Analysis Model Performed by the Researcher

Accordingly, the service life results of the model performed by the researcher, if no repair is performed on the structure, are shown in Figure 5.21 above. Correspondingly, the initiation of considerable corrosion to the steel reinforcement is predicted to happen after 34.7 years and spalling of concrete after 40.7 years from the construction date of the building. Since the building is 37 years old as of January 2013, the service life of the repaired structure is 40.7 – 37 = 3.7 years with significant corrosion commencing before 34.7 – 37 = -2.3 years from the designed initiation period of the service life.

Hence, in case no repair is done, the life expectancy of the building as per the researcher's results of the building is within the range of: 3 ± 1 years. The reasoning behind the higher result gained by the researcher's model is due to the fact that minimum cover and minimum dimensions enforced by the program are higher than the ones performed by eFORCE team. The latter is probably due to the difference in software versions used, whereas eFORCE team used version 2.0.1, while the researcher's version was 2.2.2 as seen in Appendix B, Figures ED-1 to ED-7. It shall be noted that eForce team results are more reliable as they were able to use the actual values and dimensions of sections.

5.5.3 Service Life Analysis by the Researcher (if Repair is Performed)

In case repair is done, micro-concrete is embedded into the damaged areas and attached with the chipped concrete. Hence, the years to build to the maximum chloride concentration is extended by 10 years and is assumed to be 47 years instead of 37 years as illustrated in Figure 5.22 below:

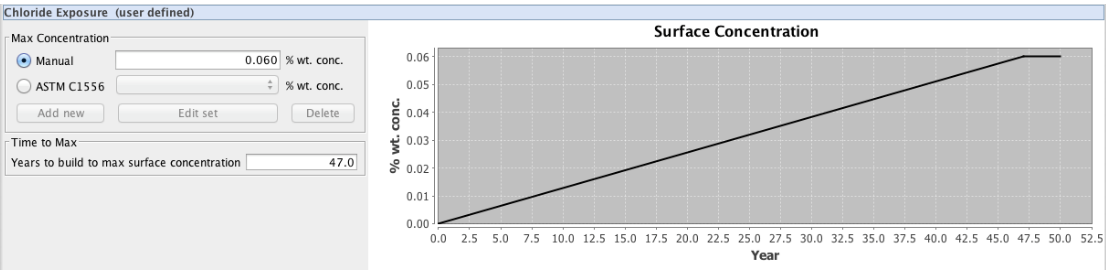


Figure 5.22 – Chloride Surface Conc. Build-up in the Researcher's Model (if Repaired)

The model of the repaired structural element in Figure 5.23 below anticipated the initial spalling of concrete to arise after 49.2 years, while the initiation of considerable corrosion of reinforcement is expected to occur after 43.2 years.

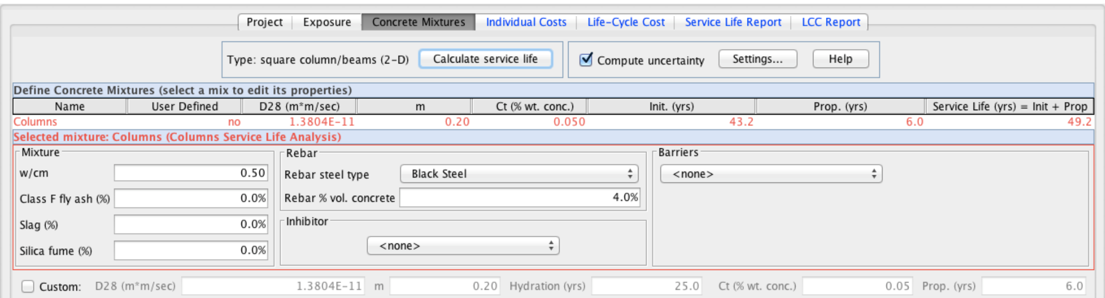


Figure 5.23 – Initiation of Corrosion and Service Life (yrs) if Repair is Performed

Accordingly, the initiation of considerable corrosion to the steel reinforcement is predicted to happen after 43.2 years and spalling of concrete after 49.2 years from the construction date of the building. Since the building is constructed 37 years ago as of January 2013, the extended service life in the researcher model (Figure 5.23) is found to be 49.2 – 37 = 12.2 years. Meanwhile, the corrosion of reinforcement will initiate after 43.2 – 37 = 6.2 years from reparations of the columns.

The service life model of the repaired structural element showing the initiation and propagation periods of the analyzed structure is illustrated in Figure 5.24 below:

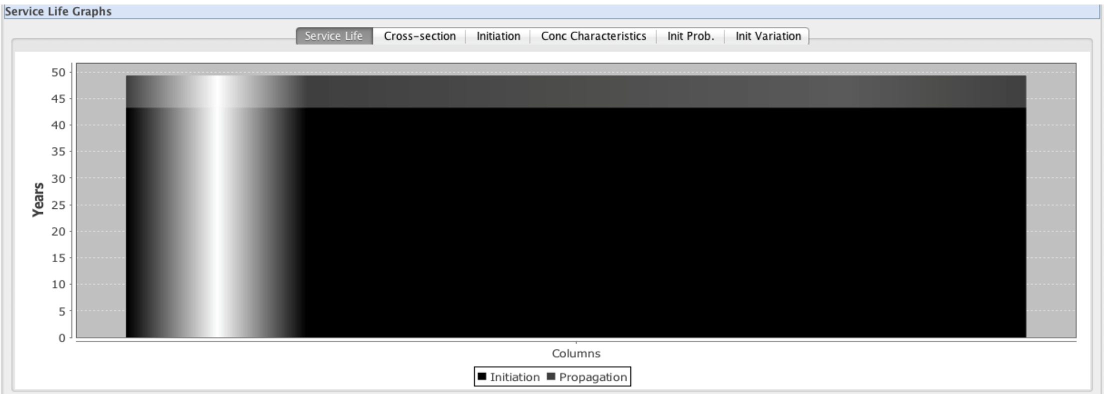


Figure 5.24 – Service Life of the Repaired Structure Illustrating the IP & PP

The concrete cross-section presenting the chloride concentration build-up and saturation degree as a percentage of concrete's weight up to the end of its initiation period is illustrated in Figure 5.25 below:

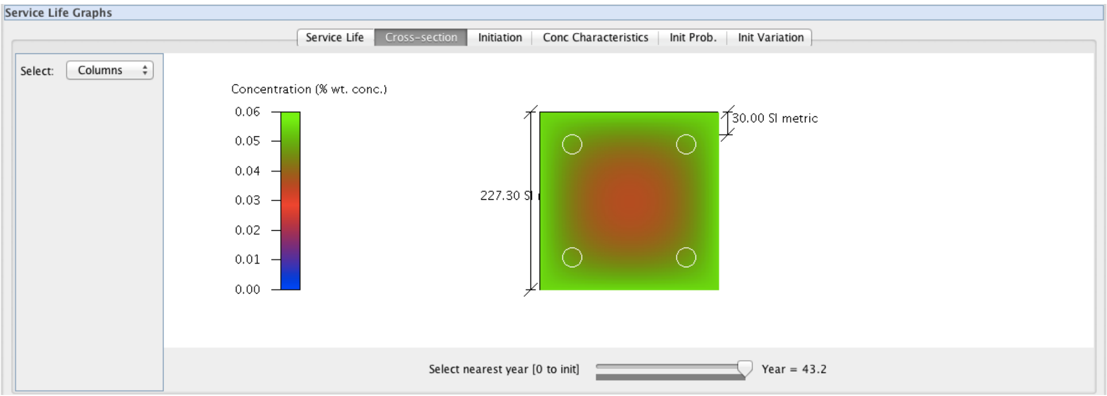


Figure 5.25 – The Chloride Concentration of the Reinforced Concrete Column at IP

The concentration of chlorides (on the vertical axis) at each depth of the analysed columns at the time of initiation as well as the level of chlorides variations at the reinforcing steel (on the vertical axis) at each point in time up to the time of initiation respectively are illustrated in Figure 5.26 below:

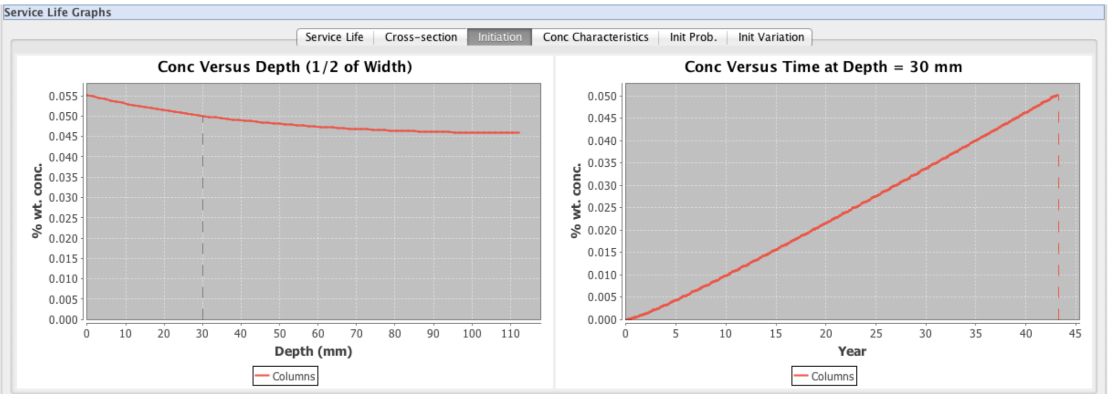


Figure 5.26 – Conc. of Chlorides at Each Depth of the Structure
& the Level of Chlorides at the Reinforcing Steel with Time Respectively

On the other hand, the diffusivity of the concrete and the change in chloride concentration on the surface of the concrete structure over time respectively are illustrated in Figure 5.27 below:

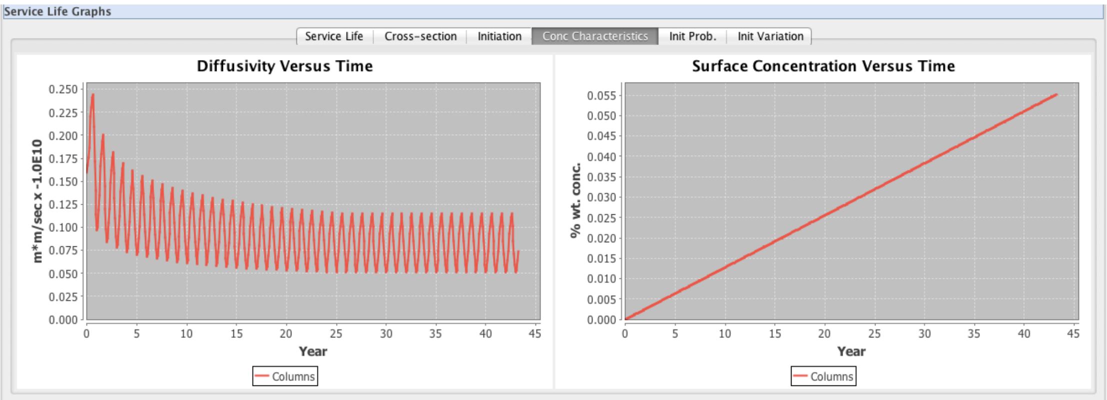


Figure 5.27 – The Diffusivity of the Concrete and the Change in Chloride Conc.
At the Concrete Surface Over Time Respectively

Meanwhile, the uncertainty computations outcomes expose the probability density functions of the service life and the cumulative density functions are illustrated in Figure 5.28 below:

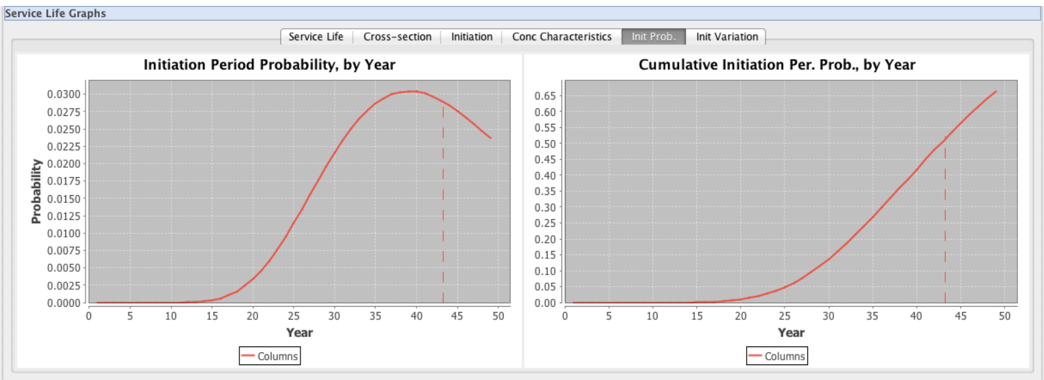
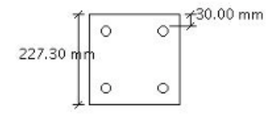


Figure 5.28 – Uncertainty Graphs
Illustrating the Initiation Period Probability (by Year) and the Cumulative Initiation Period Probability (by Year)

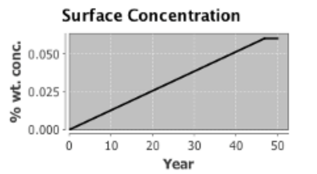
The model illustrated in Figure 5.29 below considered values of outer dimensions and clear cover as 227 mm and 30 mm respectively. It is predicting a service life with a value of 49.2 years.

Life-365 v2.2 - Concrete Mixes and Service Lives

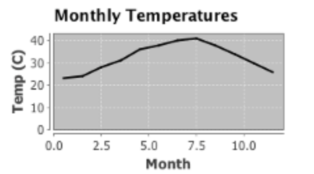
Project: Mohamed Khalfan Kherbash Building in Abu Dhabi
Description: Columns Analaysis
Analyst: Eng. Anas Dibsi
Date: 20/06/2017



square column/beams (2-D)
Outer dim: 227.3mm; clear cover:



Max surface: 0.060 % wt. conc.
Years to buildup: 47



Loc: user-defined
Type: user-defined

Concrete Mixes

Alt name	User?	w/cm	SCMs	Inhib.	Barrier	Reinf.
Columns		0.5				Black Steel

"n/a" indicates that, since the user is specifying the diffusion properties of this mix, this value is not specified.

Diffusion Properties and Service Lives

Alt name	D28	m	Ct	Init.	Prop.	Service life
Columns	1.38E-11 m*m/sec	0.2	0.05 % wt. conc.	43.2 yrs	6 yrs	**49.2 yrs**

"->" indicates that the user has directly specified this value; "+" indicates the service life exceeds the study period.

Figure 5.29 – Service Life Analysis Model if Repair is Performed as Analysed by the Researcher

Accordingly, the service life results of the model performed by the researcher, if repair is done on the structure, are shown in Figure 5.29 above. Correspondingly, the initiation of considerable corrosion to the steel reinforcement is predicted to happen after 43.2 years and spalling of concrete after 49.2 years from the construction date of the building. Since the building is 37 years old as of January 2013, the extended service life of the repaired structure is (49.2 – 37) = 12.2 years with significant corrosion commenced after 43.2 – 37 = 6.2 years from the originally designed initiation period of the structure's service life. It shall be noted that the actual extended life from the designed value is 49.2 – 40.7 = 8.5 years only.

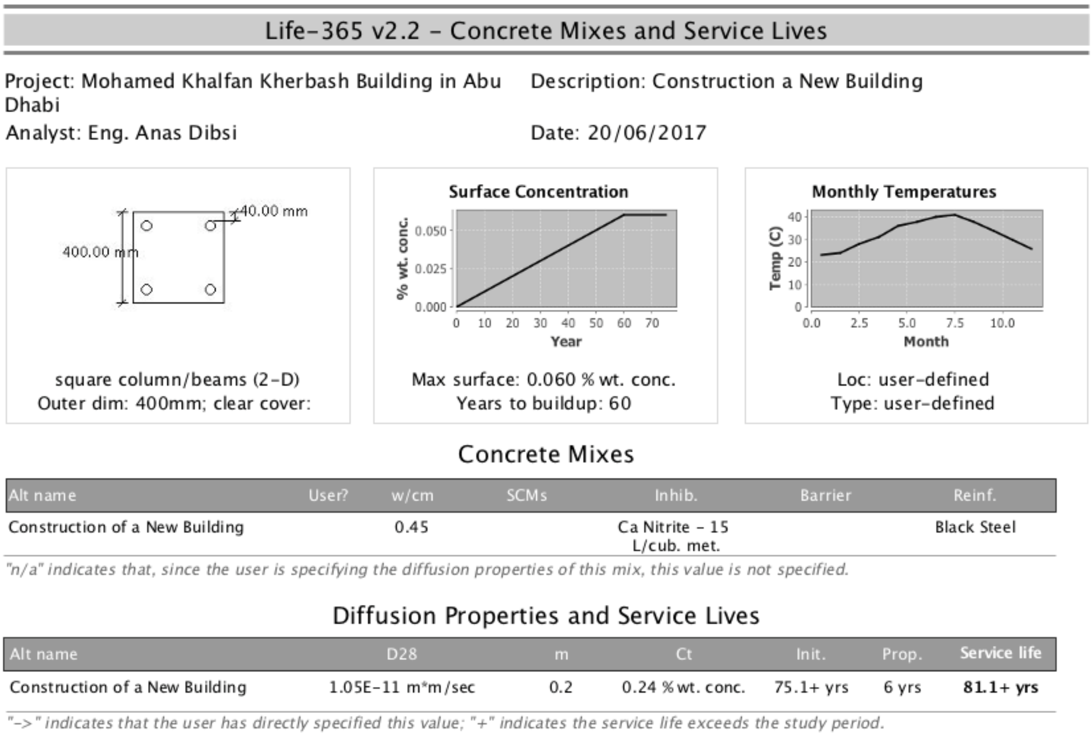
Hence, in case repair is done, the extended life expectancy of the building as per the researcher's results is within the range of: 12 ± 1 years and 8 ± 1 years from the actual service life designed value. The reasoning behind the higher result gained by the researcher's model than eFORCE Team results is due to the fact that minimum cover and minimum dimensions enforced by the program are higher. The latter is probably due to the difference in software versions used, whereas eFORCE team used version 2.0.1 as seen in Appendix B, Figures ED-1 to ED-7, while the researcher's version was 2.2.2

5.5.4 Service Life Analysis Model for Constructing a New Building with CI

In the feasibility study following the service life model considering demolishing and rebuilding option, the researcher utilizes a corrosion inhibitor (CI) additive in the newly built structure and compares it accordingly with a new model of life cycle costing to determine the most effective and efficient solution. However, due to the wide range of inhibitors available in the market, the researcher analysis restrict and limit the analysis to the latest type of corrosion inhibitor (CI) that was recently used in the tallest tower in the world, Burj Khalifa. The latter inhibitor is considered an environmentally friendly product and is manufactured by Cortec Corporation. Using a corrosion inhibitor (CI) in newly constructed structures could extend the service life of the structure significantly.

In the service life model for the demolishing and reconstructing of the structure option, the researcher considered a modification of the column and cover dimensions to 400 mm and 40 mm respectively to achieve a consistent design in accordance with ACI-318. Meanwhile, the researcher considered the addition of corrosion inhibitor (CI) manufactured by Cortec Corporation to prolong the service life of the structure. Accordingly, the time for chlorides to build to maximum concentration is increased by 62% and set to 60 years instead of 37 years as specified by Eng. Ashraf Hasania from Cortec Industries. In addition, the diffusion rate (D28) is automatically calculated as 1.047×10^{-11} for concrete with water/cement ratio of 0.45 (Hasania, 2016; Cortec MCI Brochure, 2016; Life-365 program).

The amount of Cortec MCI corrosion inhibitor (CI) to be used is 15 litres per cubic meter in accordance with the test result report performed by American Engineering Testing, Inc (January, 2011). The resulting service life model is illustrated in Figure 5.30 below:



Life-365 v2.2 – Concrete Mixes and Service Lives

Project: Mohamed Khalfan Kherbash Building in Abu Dhabi
Description: Construction a New Building
Analyst: Eng. Anas Dibsi
Date: 20/06/2017

Concrete Mixes

Alt name	User?	w/cm	SCMs	Inhib.	Barrier	Reinf.
Construction of a New Building		0.45		Ca Nitrite - 15 L/cub. met.		Black Steel

"n/a" indicates that, since the user is specifying the diffusion properties of this mix, this value is not specified.

Diffusion Properties and Service Lives

Alt name	D28	m	Ct	Init.	Prop.	Service life
Construction of a New Building	1.05E-11 m*m/sec	0.2	0.24 % wt. conc.	75.1+ yrs	6 yrs	**81.1+ yrs**

"->" indicates that the user has directly specified this value; "+" indicates the service life exceeds the study period.

Figure 5.30 – Service Life Model Results (Constructing a Building with Corrosion Inhibitor)

5.6 Discussion of Test Results

The quality of concrete and possibility of corrosion to the steel reinforcements were assessed by choosing random samples. The results of the tests performed by eFORCE revealed the maximum designing of concrete strength is based on the coring results and shall consider the minimum f_{cu} attained for a specific type of structural element.

$$f_{cu} = \frac{1.5\ (Estimated\ in - situ\ Cube\ Stregnth)}{1.2} \qquad \text{Equation 5-1}$$

The f_{cu} can be calculated from the cube compressive strength test as performed in Table 5-1 utilizing equation 5-1 as per BS 6089:1981 as follows:

Core No.	C1	C2	C3	C4	C5	C6
Estimated cube design compressive strength (N/mm^2) As per BS 6089:1981	16.125	18.375	18.5	20	18.25	15.625

Table 5-13 – Concrete Design Compressive Strength (Calculated)

Accordingly, the concrete columns from samples C1 to C5 shall be modeled for a maximum strength f_{cu} not exceeding 16 N/mm^2, while the maximum strength of pile caps and slabs shall be modeled utilizing a maximum strength f_{cu} not exceeding 15 N/mm^2 as resulted in Table 5-13. On the other hand, the range of cover in accordance with the investigation carried (Table 5-2) is between 19.8 and 25 mm, and the average concrete cover attained from the columns was 22.4 mm (eFORCE reported it as 21 mm). The latter is against ACI-318 and BS-8110 codes that suggest a minimum of 30 mm for the columns cover.

On the other hand, the results of the cover meter survey (Table 5-2) reveals that the ground floor exterior column that is subjected to severe environmental conditions and vast humidity levels acquires the lowest cover value of 11.5 mm, while the interior columns in the upper floors sustained cover dimensions range between 24 and 34.5 mm. The upper floors seems to secure a higher cover, which is consistent considering that the deterioration of the cover and delamination of the column concrete surface could be a result of water leakage that is directed downward due to gravitational forces.

Since the columns design compressive strength f_{cu} is 16 N/mm^2, while the compressive strength (f_{cu}) for the design compressive strength for slabs is 15 N/mm^2, the results presented a very low value of compressive strength due to the level of deterioration of the structure's concrete. By examining the minimum compressive structural requirement for residential building utilizing ACI-318 and BS 8110, we note that the tested cores do not achieve the minimum compressive strength of the slabs and columns, whereas the minimum compressive strength for slabs and columns should not be less than 3000 psi (21 N/mm^2) and 3500 psi (25 N/mm^2) respectively. Thus, structural design modeling shall be carried out prior and after the repair of various structural elements to reach the minimum design criteria. The new design model that is ought to be performed to ensure the safety of structure after rehabilitation.

Meanwhile, the carbonation depth possessed by the structural elements is higher than the depth of the embedded steel reinforcements, which implies that the steel reinforcements are at high risk of corrosion. Therefore, the reinforcing steel is not protected against corrosion.

Similarly, the chloride content in the columns and pile cap samples tested was found to be within the acceptable limits except in the first and fourth floor columns as well as the pile cap (Table 5-4). Correspondingly, the chlorides content found in the concrete is higher than the allowable limits and exceeding the depth of the cover, whereas the pile cap cover from 0 to 25 mm depth reached a critical point, while the first and forth columns exceeded the maximum allowable chloride ion content at 50 to 75 mm depth. Thus, the reinforcement is at a high risk of corrosion in these regions. The latter is particularly significant in the tested columns cores since their cover dimension is less than the depth of the allowable chloride ion limit. Hence, in order to repair the concrete, the structural reinforcing steel should also be exenterated from rust and protected from further corrosion.

However, the probability of corrosion in the steel reinforcement as per the half-cell potential test performed on the ground floor and first floor columns (T1 and T2) revealed that the probability of corrosion in these unprotected columns is uncertain (Table-5-6). Although the previous test results revealed the unlikelihood of corrosion, the concrete visual inspection, as well as the quality tests presented earlier in Table 5-8 revealed that the exposed structure sustained an immense degree of corrosion in different structural elements and poor quality of the original concrete respectively.

However, since the half-cell potential test performed on the ground and first floor column revealed values that suggests the unlikeliness of corrosion, an inconsistency in the report values is found as the chloride test performed on the first floor column presented high chloride ions percentage compared to the cement mass reaching up to 0.3570% and exceeded the maximum allowable rate of 0.30% for OPC reinforced concrete (as per the maximum allowable by ACI 318-95 [124]). Moreover, the visual inspection revealed that the concrete in structural elements failed due to high level of reinforcement corrosion.

Additionally, comparing the results in Table 5-10 with the interpretations in Table 5-9 from performing the resistivity test yielded the unlikelihood of corrosion to occur in the interior columns of the ground floor. While the risk of corrosion is low in the fourth column, the ground floor exterior column and first floor column are susceptible to a moderate to high risk of corrosion.

Equally, the quality of concrete is determined by the Ultrasonic Pulse Velocity test. The ultrasonic pulse velocity test performed on the existing concrete in the structure was based on BS EN 12504-4:2004. The test revealed results varied between 347 m/s and 2054 m/s. It shall be noted that all results presented were lower than the medium quality grading (3000 m/s – 3500 m/s), whereas the concrete quality grading on average was 1411 m/s. This means that the concrete quality test yielded very poor concrete quality.

5.7 Comparison Discussion on the Service Life Models

Both eFORCE team and the researcher modeled the structure on Life-365 attaining results that were presented in this study in Figures ED-7 and ED-4, Appendix B for eFORCE model and Figures 5.21 and 5.29 for the researcher's model. It is also vital to note that due to the lack of available data on the pile cap, the modelling could only be performed on the columns. It should be noted that the Life-365 model performed by the researcher does not accepts width (outer dimension) and clear cover values of the square columns/beams (2-D) as introduced by the eFORCE team model, whereas the minimum width value for square columns that is accepted by the model is 227.3 mm, while the width model presented in the report is 200.0 mm. Similarly, the input cover values introduced by the researcher is 30.0 mm while the one introduced by the researcher is only 21 mm. The difference is most probably due to the Life-365 software version difference as discussed earlier.

As the eFORCE team model in Figure ED-7, Appendix B, in case no repair is done, presented a lower value in outer dimensions and clear cover than the model performed by the researcher as illustrated in Figure 5.21, it is predicting a lower service life with a value of 38.3 years than the researcher's model (40.7 years). This is consistent considering that a lower cover will result in a higher corrosion of the steel reinforcement and eventually a higher deterioration rate for the same type of concrete. Therefore, the initial spalling in eFORCE team model anticipated the initial spalling of concrete to arise after 38.3 years in the model, while the researcher's model in Figure 5.21 expected the first spalling to occur after 40.7 years. On the other hand, the initiation of considerable corrosion of reinforcement is expected to occur after 32.3 years in eFORCE model, while it is 34.7 years in the reasearcher's model. The values are close and reliable since the researcher's model is limited with a higher cover and wider element section than the analyzed by eFORCE team.

Accordingly, in case no repair is done, the life expectancy of the building as per eFORCE team is 38.3 – 37 = 1.3 years, which mean that the expectancy can range from 1 ± 1 years, while the researcher's results present that the life expectancy of the building is 40.7 – 37 = 3.7 years, which mean that the expectancy is in the range from 3 ± 1 years. As stated earlier, the reasoning behind the higher result gained by the researcher's model is due to the fact that minimum cover and minimum dimensions enforced by the program are higher than the ones performed by eFORCE team. The latter is probably due to the difference in software version used, whereas eFORCE team used version 2.0.1 as seen in the data inserted by eForce Team in Appendix B, Figures ED-1 to ED-7, while the researcher's version was 2.2.2.

The service life results of the model performed by eFORCE team, in case repair is performed on the structure, is shown in Figure ED-4, Appendix B. Accordingly, the initiation of considerable corrosion to the steel reinforcement in eFORCE team is predicted to happen after 40.7 years and the spalling of concrete after 46.7 years from the construction date of the building. Since the building is 37 years old as of January 2013, the extended service life of the repaired structure is expected to be 46.7 – 37 = 9.7 years with significant corrosion commencing after 40.7 – 37 = 3.7 years. Thus, the life the expectancy can range from 9 ± 1 years.

On the other hand, the service life results of the model performed by the researcher, if repair is performed on the structure, are illustrated in Figure 5.29. Accordingly, the initiation of considerable corrosion to the steel reinforcement is predicted to happen after 43.2 years and spalling of concrete after 49.2 years from the construction date of the building. Since the building is 37 years old as of January 2013, the extended service life of the repaired structure is expected to be 49.2 – 37 = 12.2 years (actual from designed life is 49.2 – 40.7 = 8.5 years) with significant corrosion commencing after 43.2 – 37 = 6.2 years from repairing the structure. Thus, the life the expectancy can range from 12 ± 1 years. It shall be noted that the assessment shall be performed again after 10 years from reparation of the structure to ensure the capability of the building to sustain any additional years to the life expectancy.

Consequently, the data presented by eFORCE team model is deemed more accurate due to the varied difference in width and cover dimensions input into the model. It is also vital to note that due to the lack of available data on the pile cap, the modelling could not be performed.

If demolishing and reconstructing the structure is considered an option, the service life model presented in Figure 5.30 suggests that the initiation of considerable corrosion to the steel reinforcement is predicted to happen after 75.1+ years and spalling of concrete after 81.1+ years from the construction date of the building. Thus, if the building is demolished and reconstructed, the service life of the structure is expected to be 81.1+ years depending on the propagation period.

5.8 Life Cycle Cost Assessment Performed by the Researcher

The life cycle cost assessment is based on data gathered from well-experienced teams from Golden Planners Consultants, Abu Dhabi Commercial Engineering, BASF Industries, and Sika Industries in the market in terms of demolition costs, construction costs and rehabilitation costs.

5.8.1 Demolition and Reconstruction vs. Rehabilitation

While the demolition and reconstruction costs are not fixed and fluctuated by the market, the researcher performed an intense investigation and interviews with both teams from Golden Planners Engineering Consultants (GPC), Abu Dhabi Commercial Bank (ADCE), and Kiwan Demolishing Contracting Company. Consequently, all parties agreed that the demolition costs for the said case study ranges between 200,000 AED and 350,000 AED depending on the local authorities regulations in the located plot and the availability of sufficient area surrounding the building.

Eng. Kenan Abbas from Kiwan argued that factors affecting the demolishing costs could be affected by surrounding parking availability and rental parameters from the governmental authority Mawaqif, equipment manoeuvre spacing surrounding the plot, and the amount and price of the scrap materials in the plot. On the other hand, Arch. Roger Zehil from ADCE stated that they are facing a lot of difficulties in determining a value for demolishing works for buildings due to the introduction of new regulations by Abu Dhabi Municipality every year.

Meanwhile, according to Arch. Ahmad Wafai from GPC, the reconstruction cost of a building similar to the one in the case study could range between 3600 AED/sq.m to 4200 AED/sq.m for typical floors, while the cost for services floors (such as parking floors) cost ranges between 2400 AED/sq.m and 2600 AED/sq.m. The cost of each component depends on the material and finishing used in the building. He added: "most of the city's low to medium rise constructions are undertaken by ADCE, and the latter has a maximum total price of 4000 AED/sq.m".

On the other hand, rehabilitation of deteriorated concrete structures is a newly introduced concept in the GCC region as the construction boom was basically during the past 40 – 50 years only. According to Arch. Mustafa Shawa and Eng. Ghusson Al Lakoud from GPC: "fifty years ago, there were barely any construction in the United Arab Emirates, and therefore, there are no previous rehabilitation of deteriorated concrete structures data that are readily available in hand. However, many constructions that were built in the past few decades are deteriorating and require immediate attention."

5.8.2 Costs of Various Building Materials

The costs of the building and construction materials used in this study are based on the current data attained from Statistics Center Abu Dhabi (SCAD) [142]. Accordingly, the researcher used the Construction Cost Index (CCI) for the first quarter (Q1) of the year 2016 and the first quarter (Q1) of the year 2017 and the Building Material Price Tables (BMPs) dated April 2017 in determining the various costs of various building materials. In general, the Construction Cost Index (CCI) serves as an indicator of the average cost change during a period of time of specific commodities and services associated with the construction sector (Swarup, 2017; SCAD, 2016) [141,142,143]. The building material prices considered in this study are strictly the building materials with the workmanship prices and excludes any finishing or other engineering disciplines fields as outlined in Table 5-14 below:

Sr. No.	Commodity	Average Price (AED)
1	Concrete Ready Mix / Normal (newton 40) / m^3/ U.A.E.	222
2	Concrete Ready Mix / Sulphate Resistance / m^3/ U.A.E.	225
3	Steel / High tensile Steel / Ton / U.A.E.	1830
4	Bitumen / 50/40 / Ton	1120
5	Workmanship per person	8.5 - 20

Table 5-14 – Construction Materials Pricing Considered

Source: Statistics Center Abu Dhabi, 2017 [142]

On the other hand, the repairing cost utilizing micro-concrete ACMs is 1000 AED/sq.m as informed by Eng. Mahmoud Atteya from Sika U.A.E. L.L.C. through email communication dated 27th February 2017. Meanwhile, the percentage weights and CCIs are outlines in Table 5-14 as follows:

Main construction groups	Weight	CCI for Q1 2016	CCI for Q1 2017
Construction materials	13	86.6	86.5
Finishing materials	26	100.2	104.8
Electrical works materials	8	97.4	100.9
Mechanical works - plumbing and drainage materials	4	101.2	101.7
Mechanical works - fire fighting	3	114.5	114.5
Mechanical works - A/C	7	100.4	104.2
Equipment	2	113.5	134.2
Manpower	29.5	90.4	78.3
Services	4.5	84.4	89.1
Finances and bonds	3	100.0	100.0

Table 5-15 – Construction Components Weight & CCI for Q1 of 2016 and 2017

Source: Statistics Center Abu Dhabi [143]

In accordance with the Statistics Center Abu Dhabi, the percentage weights attained from the CCI for the component cost of construction of structures in the UAE is illustrated in Figure 5.31 below:

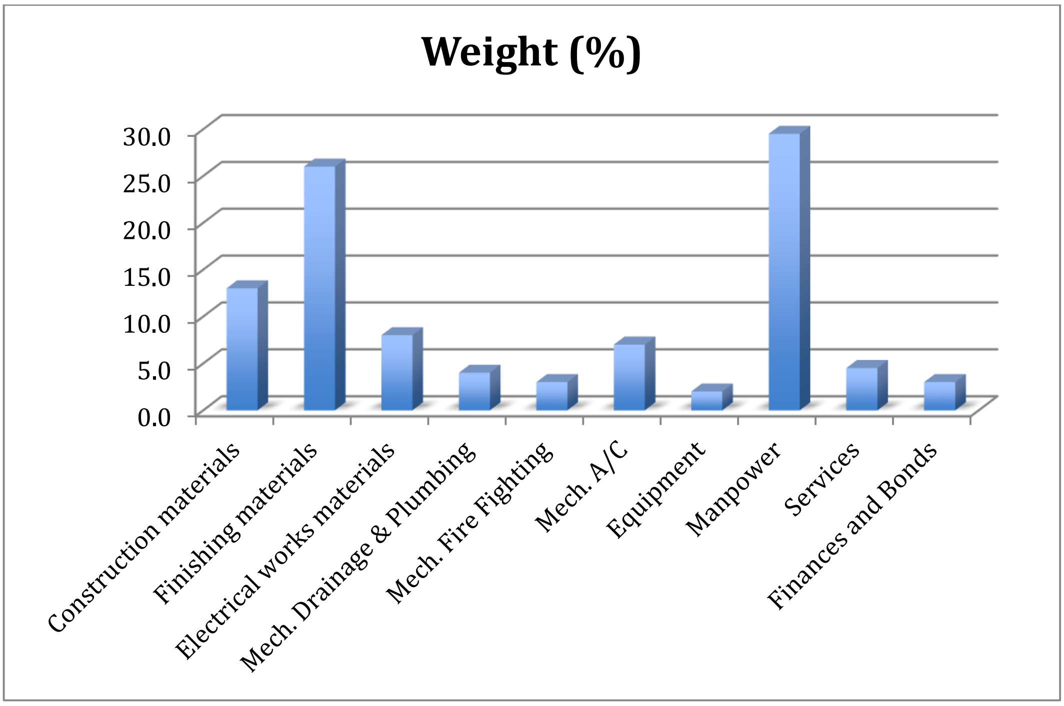


Figure 5.31 – Percentage Weights of Construction Components (April, 2017)

From Table 5-14 and Figure 5.31, we note that the most crucial items influencing the construction cost index are the manpower, finishing materials, and construction materials respectively. While the weights are almost fixed on yearly basis, the component construction cost index between the first quarter (Q1) of the year 2016 and the first quarter (Q1) of the year 2017 differs by 3.2% and are illustrated in Figure 5.32 below:

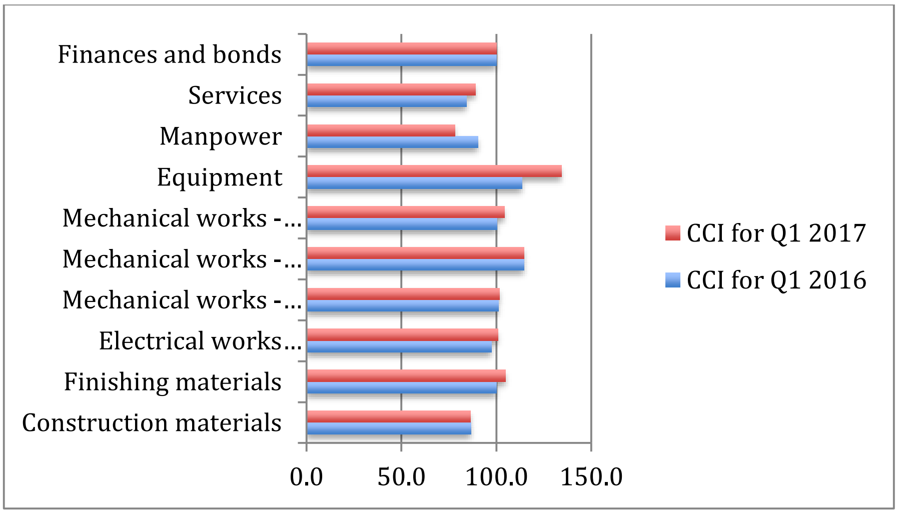


Figure 5.32 – Comparison of CCI between Q1 for 2016 and Q1 for 2017

5.8.3 Life Cycle Cost Analysis for Repaired Service Life Model

Following to the service life model analysis previously done by the researcher on the columns, and the economical data attained from Statistics Center Abu Dhabi, the researcher performs the Life-Cycle Cost (LCC) of the repaired structure and the extended service life is compared with the demolishing and rebuilding service life model in terms of the overall cost. In the feasibility study considering the demolishing and rebuilding option, the researcher utilizes a corrosion inhibitor (CI) additive in the newly built structure and compares the overall costs based on the data attained earlier from the statistics center. Accordingly, the life cycle costing is determined to achieve to the most effective and efficient solution. As stated earlier, due to the wide range of inhibitors available in the market, the researcher analysis shall restrict and limit the analysis to the latest type of corrosion inhibitor (CI) that was recently used in the tallest tower in the world, Burj Khalifa. The latter inhibitor is environmentally friendly and is manufactured by Cortec Corporation.

The concrete and repair unit pricing of the concrete repair in comparison with the initial construction cost was taken in accordance to the email communication of Eng. Mahmoud Atteya from Sika UAE LLC reflecting the current market estimations (in US Dollars) in the United Arab Emirates. The area of repair from previously carried out visual inspection suggests that the area of repair in columns ranges from 15% – 25% of the assessed building. Thus, the average value of 20% is considered as a precaution towards various uncertainties that may occur during the repair as illustrated in the Figure 5.33 below:

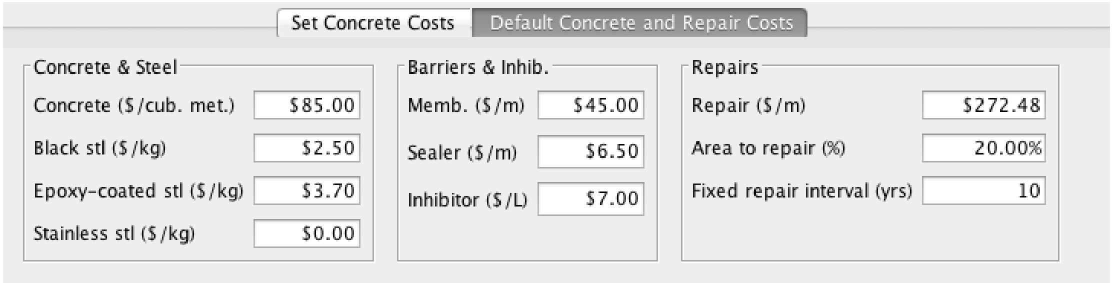


Figure 5.33 – Concrete and Repair Unit Costs

The resulting project cost from the produced model performed by the researcher on life-365 for construction for a single column (4 meters length, 227 mm in width, and 30.0 mm cover) yielded 178 $ in total, while the repairing cost yielded $198 in total as illustrated in Figure 5.34 below:

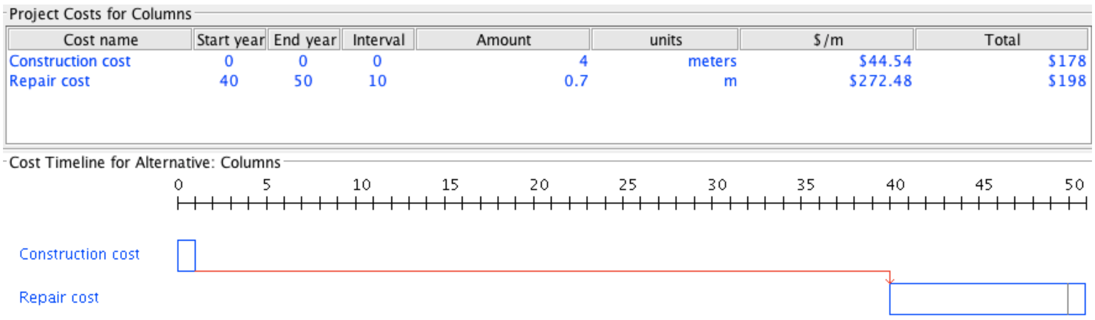


Figure 5.34 – Construction vs. Repair Cost for a Single One-Floor Column

The starting year is considered as the year of inspection performed on the building for an interval of 50 years. Considering a 50% probability on the performed model on life-365 program on the initiation period reduces the repair cost down to 134 $ for the column and resulting in a life-cycle cost of 312 $ as shown in Figure 5.35 below:

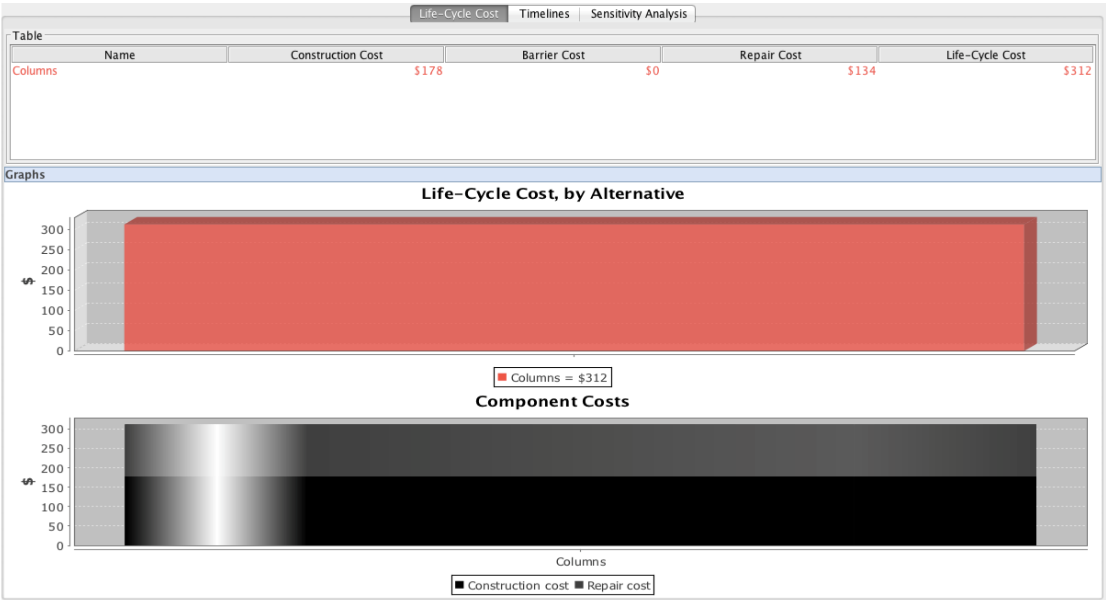


Figure 5.35 – Construction vs. Repair Cost for a Single One-Floor Column (50% Probability)

Thus, dividing the repair cost by the construction cost yields almost 75% of the original construction cost value. From the service life model performed by the researcher (if repair was performed), the actual extended service life from the designed values is 49.2 – 40.7 = 8.5 years (while 49.2 – 37 = 12.2 years was a result of the current available data in the service life analysis carried out earlier). Thus, comparing the latter result with original service life model yields an extension to the service life of 8.5/40.7 = 20.9 %. Hence, an additional 75% from the original cost towards the repair cost will result in an extension of 20.9 % of the service life for the column structural element.

5.8.4 Constant, Current, and Cumulative Values

While Life-365 is a powerful tool to attain the service life and the life cycle cost of the structural element in question, it lacks the ability to add a base year prior to 2013. Thus, the researcher took the base year of construction to be back in 2013 and analyzed a 50 years interval to attain the overall net present value. The constant costs timeline graph below illustrates the present value including all costs, by year, over the analysis period. Accordingly, summing all the costs that occurred in a specific year and then discounting the attained value to the first year utilizing the discount rate of 3% specified earlier generates these values. Whereas the cumulative present value is an extension of the constant costs graph (taking into account all the costs that have followed in the specific year with the addition of the preceding ones).

On the other hand, the current costs graph illustrates the cash flow estimated value of each cost in a specific year taking into consideration the inflation of the baseline value with the addition of the inflation rate (2%) in a given year. Whereas the cumulative current costs value is an extension of the current costs graph (taking into account all the costs that have followed in the specific year with the addition of the preceding ones) (Life-365 Manual). Therefore, if the structural element was constructed in 2013, the cumulative present value exceeds by around 75% towards the end of service life of the structure, while the cumulative current costs almost triple as illustrated in Figure 5.36 below:

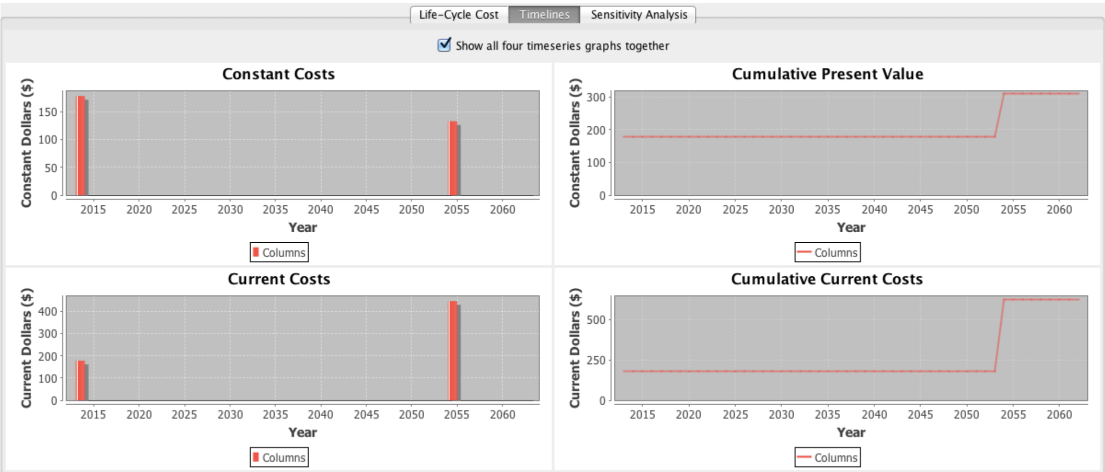


Figure 5.36 – Constant and Current Costs & Cumulative Present and Current Values

By simple mathematics (NPV = PV – Cash outflows or current costs), we note that NPV yields out a negative value. Thus, the rehabilitation of the structural element for an additional period of 8.5 years using micro-concrete advanced composite is deemed a loss.

5.8.5 Sensitivity Analysis

The sensitivity analysis is carried out based on the fundamental variables influencing the case study. These variables are identified as the inflation rate, discount rate, repair costs, area of repair, and frequency of repair intervals. Accordingly, the inflation rate (currently set at 2%) fluctuation over the life cycle cost of the structural element is illustrated in Figure 5.37 below:

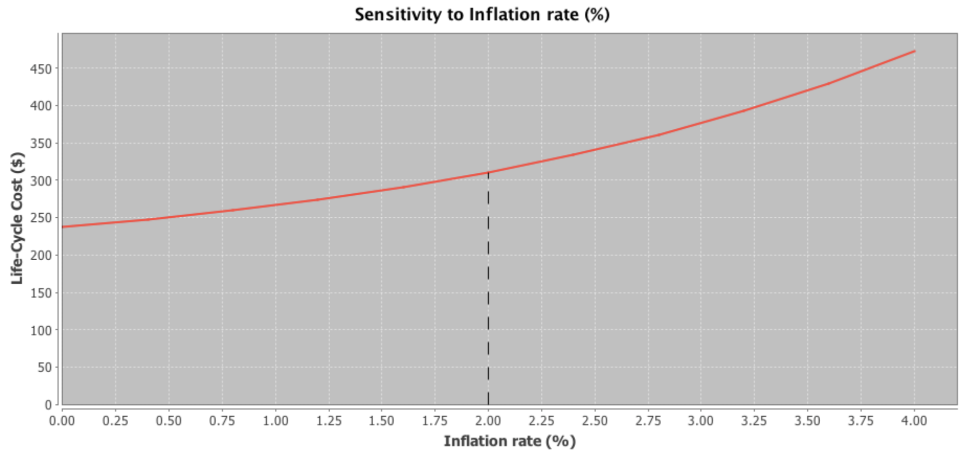


Figure 5.37 – Sensitivity to Inflation Rate (%)

We note that the inflation rate fluctuation could influence the life-cycle cost of the structure negatively if the rate increases, and therefore, it could result in ambiguities in economical values and impose uncalculated financial burdens. Meanwhile, the discount rate fluctuation and increment could influence the overall life cycle cost of the structure positively as illustrated in the sensitivity analysis of the discount rate (currently set at 3%) in Figure 5.38 below:

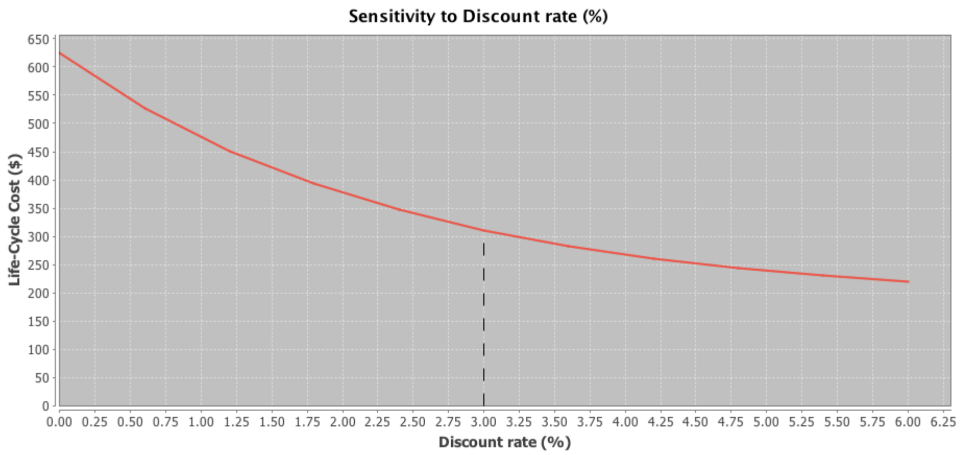


Figure 5.38 – Sensitivity to Discount Rate (%)

On the other hand, the sensitivity towards the fluctuation of the repair cost, area of reparation (20%), and fixed repair intervals are illustrated in Figures 5.39, 5.40, and 5.41 below:

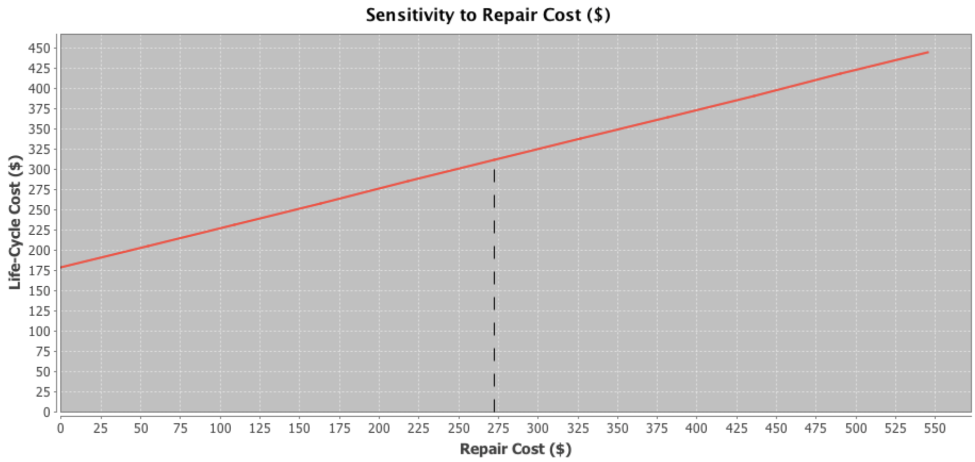


Figure 5.39 – Sensitivity to Repair Cost ($)

From Figure 5.39, we note that the variation of repair costs value could influence the over-all life cycle cost of the structure immensely. If the repair costs increases, the overall life cycle cost of the studied structure is affected significantly. The same impact applies in terms of the required area to be repaired as illustrated in Figure 5.40 below:

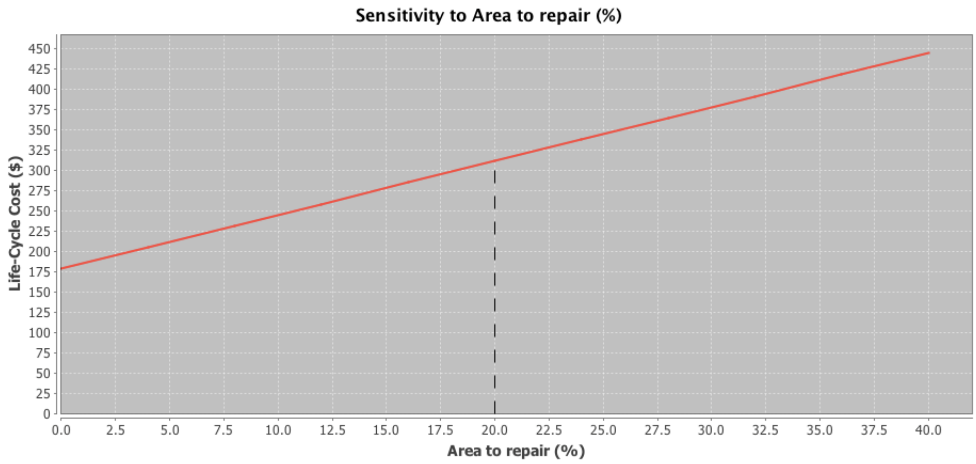


Figure 5.40 – Sensitivity to Area to Repair (%)

On the other hand, the sensitivity towards the frequency of repair intervals set at 10 years is deemed adequate, as the interval life cycle cost after 10 years is steady and stable as illustrated in Figure 5.41 below:

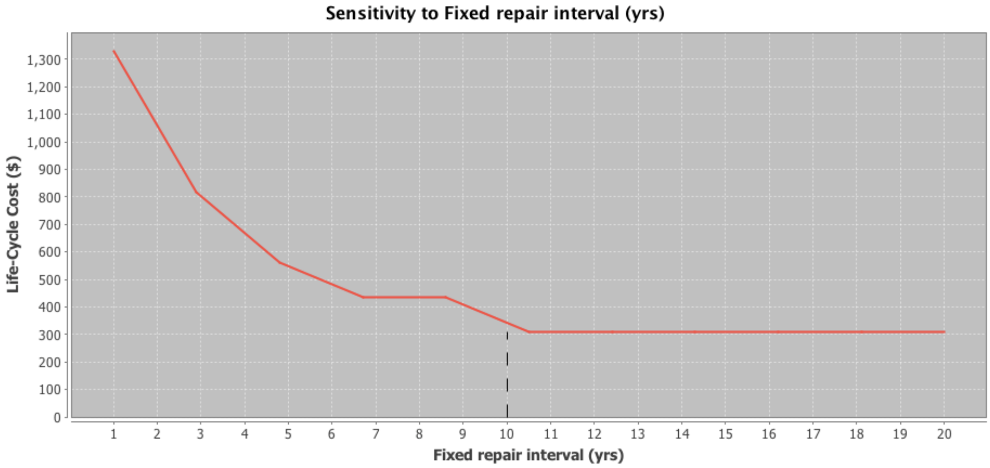


Figure 5.41 – Sensistivity to Fixed Repair Interval (yrs)

As the built-up area (BUA) of the structure is determined by the researcher in the following chapter as 6603.1 sq.m in Table 6-1, and applying the cost of repair per sq.m attained from Sika industries (1,000 AED/sq.m inclusive of material price and workmanship) results for a 20% area of repair for the case study would result in a total repair cost of 1,320,620 AED for extending the service life of the structure by 8.5 years from the actual designed service life. The revenue of the project for extending the service life of the project is negative in comparison with the actual cost as the NPV yielded a negative value.

Chapter 6

Researcher's Proposal for the Building

6.1 Researcher's Proposal

The researcher proposes the demolition and reconstruction of the building as it is deemed more cost efficient. A site visit was done by the researcher to Abu Dhabi Municipality on 21 February 2017, the number of floors in the location of the building could be increased to 16-storey tower as permitted by Abu Dhabi Aviation Authority. However, in this paper, the proposal is limited to 8-storey levels building in order to compare the repair option along with the demolition and reconstruction option efficiently.

6.1.1 Areas Breakdown

The areas breakdown based on the site plan attained from Abu Dhabi Municipality found in Appendix C and the architectural plans proposal prepared by the researcher, found in Appendix A, are presented in Table 6-1 below:

Levels		Facility	Area in m^2
A.	BASEMENT FLOORS No. of Floors : 2	Car Parking Circulation and Services **Sub Total (per floor)**	238.0 805.0 **1043.0**
B.	GROUND FLOOR	Showroom Circulation and Services **Sub Total**	26.1 372.0 **398.1**
C.	MEZZANINE FLOOR	Offices Circulation and Services **Sub Total**	163.0 209.0 **372.0**
D.	TYPICAL FLOORS No. of Floors 8	Flats (Net Area) Circulation and Services **Sub Total (per floor)**	330.0 121.0 **451.0**
F.	LOWER ROOF LEVEL	Flats Building Services **Sub Total**	0.0 139.0 **139.0**
Grand Total			**6,603.1**

Table 6-1 – Areas Breakdown based on Researcher's Plans Proposal

6.1.2 Cost of Demolishing and Reconstruction of the Building

Taking into consideration the demolition and reconstruction option of the structure and utilizing the data attained in Table 5-15 for a construction cost of 3700 AED per sq.m for the showroom, offices, and flats floors, while 2500 AED per sq.m for the car parking. Accordingly, the cost for demolition and reconstruction of the building is illustrated in Table 6-2 below:

Description		**Facility**	**Area m^2**	**Rate Dhs./sq .m**	**Sub Total Dhs.**	**Total Cost Dhs.**
A	Demolition of existing building	Lump sum (L.S) 250,000				
B	Basement Floors No. of Floors **2**	Car Parking Circulation & Services **Sub Total**	1043	2500	2,607,500	5,215,000
C	GROUND FLOOR	Showroom Circulation & Services **Sub Total**	398.13	3700	1,473,081	1,473,081
D	MEZZANINE FLOOR	Office & Showroom Circulation and Services **Sub Total**	372	3700	1,376,400	1,376,400
E	TYPICAL FLOORS No. of Floors **8**	Residential Flats Circulation and Services **Sub Total**	451	3700	1,668,700	13,349,600
F	LOWER ROOF LEVEL	Residential Flats Building Services	139	3700	514,300	514,300
Total						21,928,381
G	Consultant Fees (Design & Supervision)	22,380,094	4%			877,135
Total						**22,805,516**

Table 6-2 – Demolition and Reconstruction Cost

Consequently, the cost of each construction group in accordance with Table 5-15 and Figure 5.31 is outlined and illustrated in Table 6-3 and Figure 6.1 respectively:

Main construction groups	Weight (%)	Cost per sq.m (AED)	Total Cost as per the BUA (AED)
Construction materials	13	448.99	2,964,717.08
Finishing materials	26	897.98	5,929,434.16
Electrical works materials	8	276.30	1,824,441.28
Mechanical works - plumbing and drainage materials	4	138.15	912,220.64
Mechanical works - fire fighting	3	103.61	684,165.48
Mechanical works - A/C	7	241.76	1,596,386.12
Equipment	2	69.08	456,110.32
Manpower	29.5	1,018.86	6,727,627.22
Services	4.5	155.42	1,026,248.22
Finances and bonds	3	103.61	684,165.48
Total Cost	**100**	**3,453.76**	**22,805,516.00**

Table 6-3 – Construction Groups Cost BUA Analysis

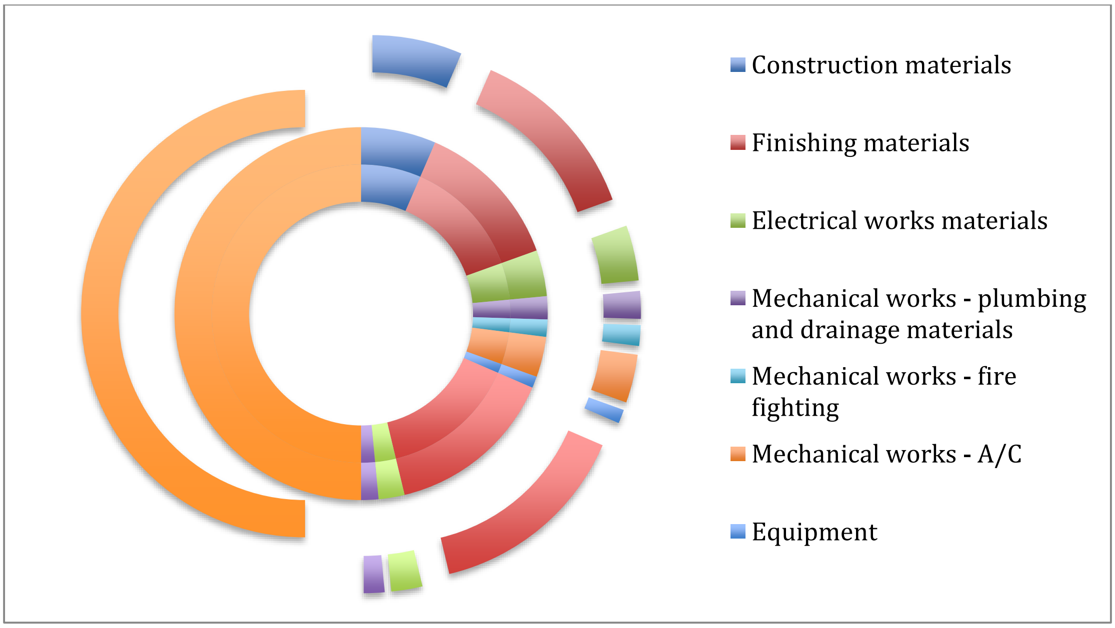


Figure 6.1 – Construction Groups Cost Analysis Chart

According to Arch. Ahmad Wafai from GPC, the workmanship (manpower) for construction materials in terms of concrete sub-structure, super-structure and block works for similar type of buildings is estimated to be 10% of the total weight of 29.5%. Accordingly, the total cost of construction civil works is 5,245,268.68 AED for a total service life of 81+ years. Comparing the latter result with the repair cost value of 1,320,620 AED for an extension of 8.5 years only on the service life of the structure clearly presents a very high opportunity cost in terms of repairing option in contrast with demolition and reconstruction option. In addition, since the building is constructed a long time ago, the finishes and MEP equipment have already deteriorated and dismantled from the project as per the figures illustrated earlier. Thus, the researcher’s proposal of demolition and reconstructing the building is deemed more efficient on the long-term economical benefit.

Chapter 7

Discussion, Conclusion and Recommendations

7.1 Discussion & Conclusion

Diverse elements contribute to the deterioration of reinforced concrete in building structures such as aging, reinforcement corrosion, humidity and oxidation, freeze-thaw events. The severe exposure conditions results in the gulf region speeds up the oxidation process in steel reinforcement that in turn results in rusting of the reinforcement. Consequently, the concrete properties get altered through the variation of applied thermal and mechanical stresses. Hence, the demand on ACMs grew to attain a more durable and sustainable structures

Although the service life and life cycle cost analysis of deteriorated concrete structures is considered a challenging task, the researcher undertook this study that examines a ground plus eight floors deteriorated building in the city of Abu Dhabi, UAE from both the overall service life of the building and rehabilitation/reparation economical evaluation. The aim of this research is to present the service life cycle and cost analysis data for modeling of the said deteriorated structure.

While the service life models without repair for models performed by eFORCE team and the researcher are predicting a lower service life in the researcher's model with a value of 38.3 years compared to 40.7 years respectively, it is considered consistent since the lower cover and width element values used by eFORCE team in their model will result in a higher corrosion of the steel reinforcement and eventually a higher deterioration rate for the same type of concrete. The initiation of considerable corrosion of reinforcement is expected to occur after 32.3 years in eFORCE model, while it is 34.7 years in the researcher's model.

Similarly, in case no repair is done, the life expectancy of the building as per eFORCE team can range from 1 ± 1 years that indicates the failure of the building and very low possibility for service life extension, while in the researcher's model, the life expectancy of the building is within the range of 3 ± 1 years. The rational following the higher result gained by the researcher's model is due to the fact that minimum cover and minimum dimensions enforced by the program are higher than the ones performed by eFORCE team. The latter is probably due to the difference in software version used, whereas eFORCE team used version 2.0.1 as seen in Appendix B, Figures ED-1 to ED-7, while the researcher's version was 2.2.2.

On the other hand, the service life results of the models performed by eFORCE team and the researcher, in case repair is performed on the structure, presents the initiation of considerable corrosion to the steel reinforcement is predicted to occur after 40.7 years and 43.2 years with spalling of the concrete after 46.7 years and 49.2 years respectively. Thus, the life the expectancy by both models can range from 9 ± 1 years and 12 ± 1 years respectively.

Consequently, the data presented by eFORCE team model is deemed more accurate due to the varied difference in width and cover dimensions input into the model. It is also vital to note that due to the lack of available data on the pile cap, the modelling was restricted to columns. It shall be noted that the assessment shall be performed again after 10 years from reparation of the structure to ensure the capability of the building to sustain any additional years to the life expectancy.

In case demolishing and reconstruction is considered an option, the service life model performed by the researcher suggested that the initiation of considerable corrosion to the steel reinforcement is predicted to happen after 75.1+ years and spalling of concrete after 81.1+ years from the construction date of the building. Thus, if the building is demolished and reconstructed, the service life of the structure is expected to be 81.1+ years depending on the propagation period.

The resulting repair cost for every deteriorated column was determined to be higher by 11.1% than the construction cost of the said column with the value for construction yielding $178 and the value of repairing yielding $198. Considering a 50% probability on the initiation period reduces the repair cost down to $134 for the column and resulting in a life-cycle cost of $312. The previous results shows that the difference in cost between rehabilitating the structure through repairs and reconstructing a new building yields a difference range between 24.7% and 32.3%. On the other hand, the sensitivity analysis revealed that the the cost influencing variables determined are the inflation rate, discount rate, repair costs, and the area of repair, the frequency of repair intervals set as 10 years is deemed adequate, stable, and does not fluctuate with time.

As the built-up area (BUA) of the structure is determined by the researcher as 6603.1 sq.m in Table 6-1, and applying the cost of repair per sq.m attained from Sika industries (1,000 AED/sq.m inclusive of material price and workmanship) results for a 20% area of repair for the case study would result in a total repair cost of 1,320,620 AED for extending the service life of the structure by 8.5 years from the actual designed service life.

On the other hand, the total cost for constructing a new building (concrete and block-works only) yields a cost of 5,245,268.68 AED for a total service life of 81+ years, while the repair cost for extending 8.5 years in the service life of the structure yields a total cost of 1,320,620 AED. The latter is 25% of the current reconstruction cost and serve merely 10.5% of the original service life of the structure. Therefore, the repairing to demolishing and reconstruction value is not sufficient and the demolishing and reconstruction option is deemed more efficient.

7.2 Recommendations and Future Trends

While ACMs opens the door for a wide range of potential possibilities in construction and rehabilitation/repair industry, the current market prices in the UAE for procurement and installation of the materials necessitated to perform the repairs are higher than the acceptable range and are yielding a negative value on the long-term investment. The main reason behind the high cost is due to the source of origin, differential currency costs, shipping, and redistributing costs.

However, as the demand grows higher on the repair ACM material, the latter will probably impose a great deal of pressure on the manufacturing businesses abroad and may ultimately lead to manufacture it locally. The researcher's recommendation to demolish and reconstruct a new structure was due to many factors, such as the market prices for rental value in old buildings are much lower than those of new ones, the originally poor design and specifications of the old building that does not consider seismic and wind loads, the non-energy/water efficient fixtures and equipment installed, the non-compliance of old buildings to the latest civil defense and other authorities safety regulations, and higher operational and maintenance costs.

In addition, the unreliability of the structural data as the construction of the building was within a decade where seawater was sometimes used in curing, which may cause sudden failures in untested areas where steel heavy steel corrosion could be hidden. Furthermore, the statistical data presented that the profitability of a repairing choice over demolishing and reconstruction is negative as determined by the value of the NPV, which yields a loss in the long term, if the repair option was chosen.

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Appendices

Appendix A: Researcher's Proposal (Constructing a New Building) Plans

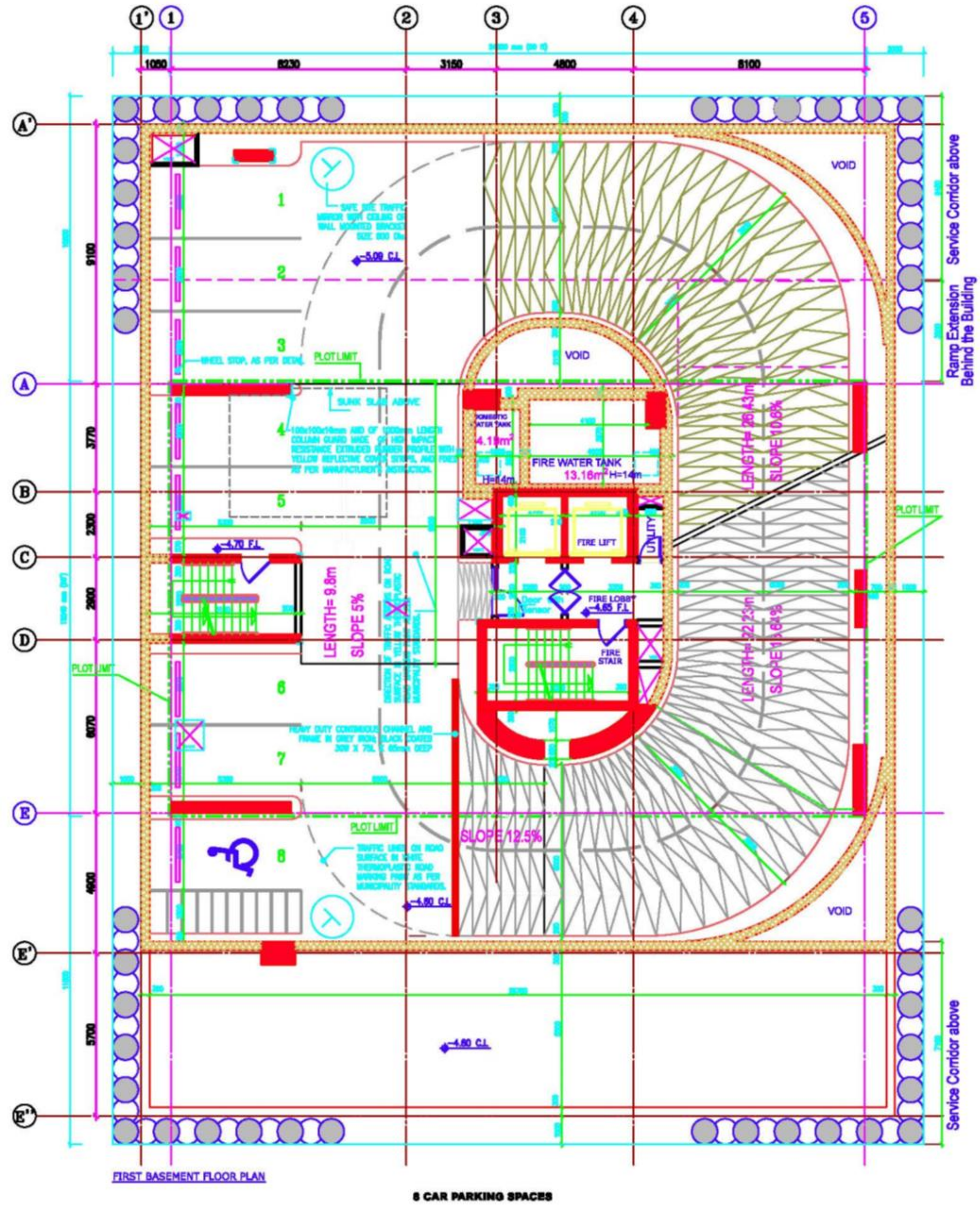


Figure A1. First Basement Floor Plan

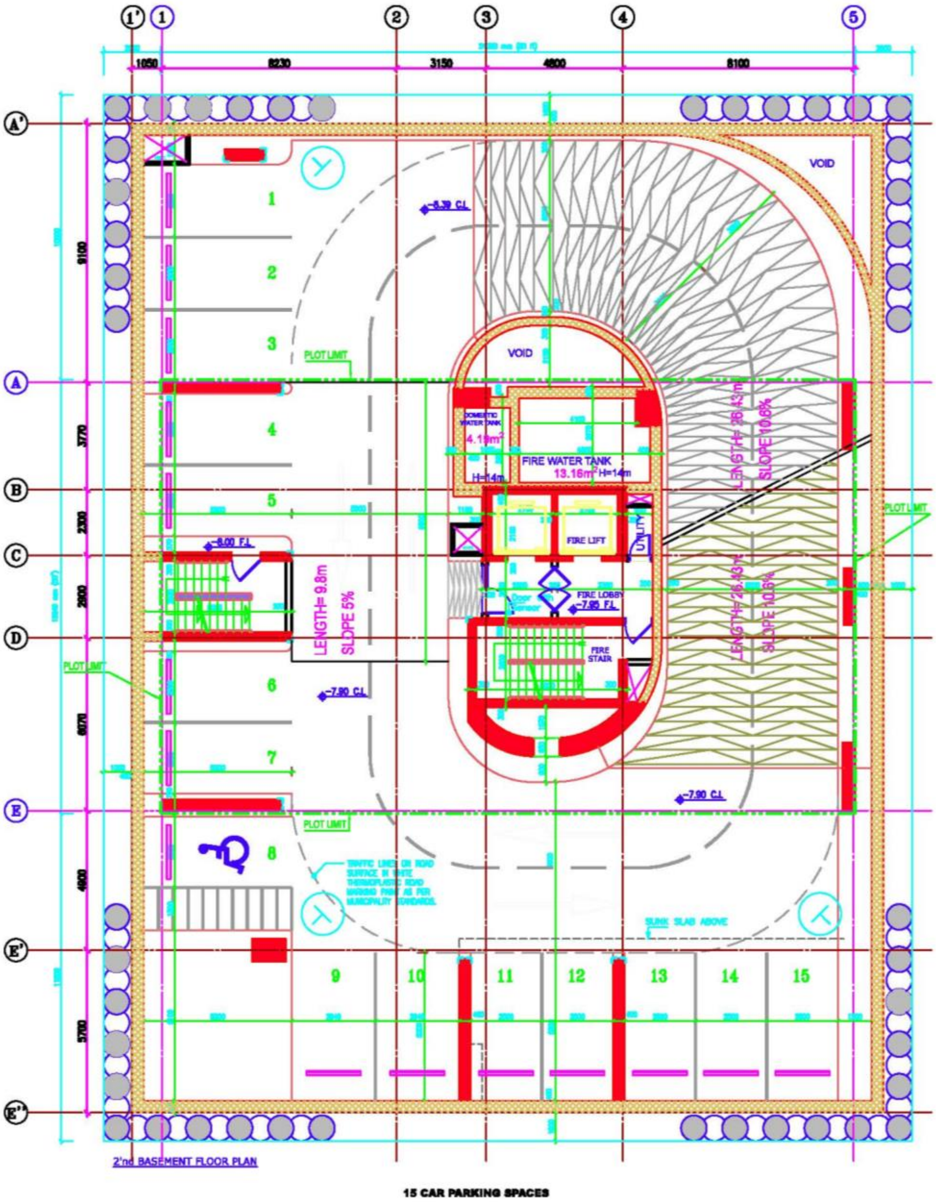


Figure A2. Second Basement Floor Plan

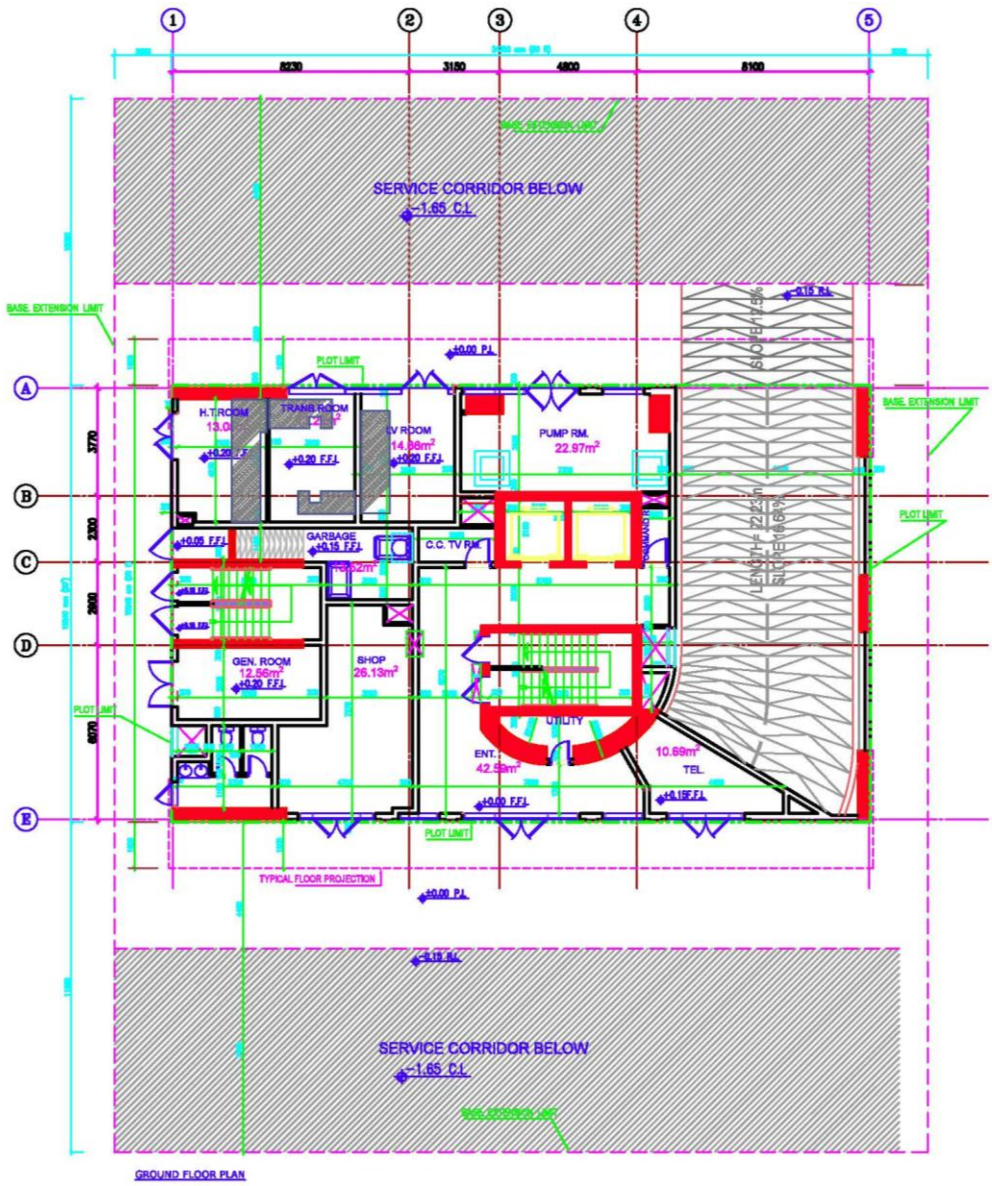


Figure A3. Ground Floor Plan

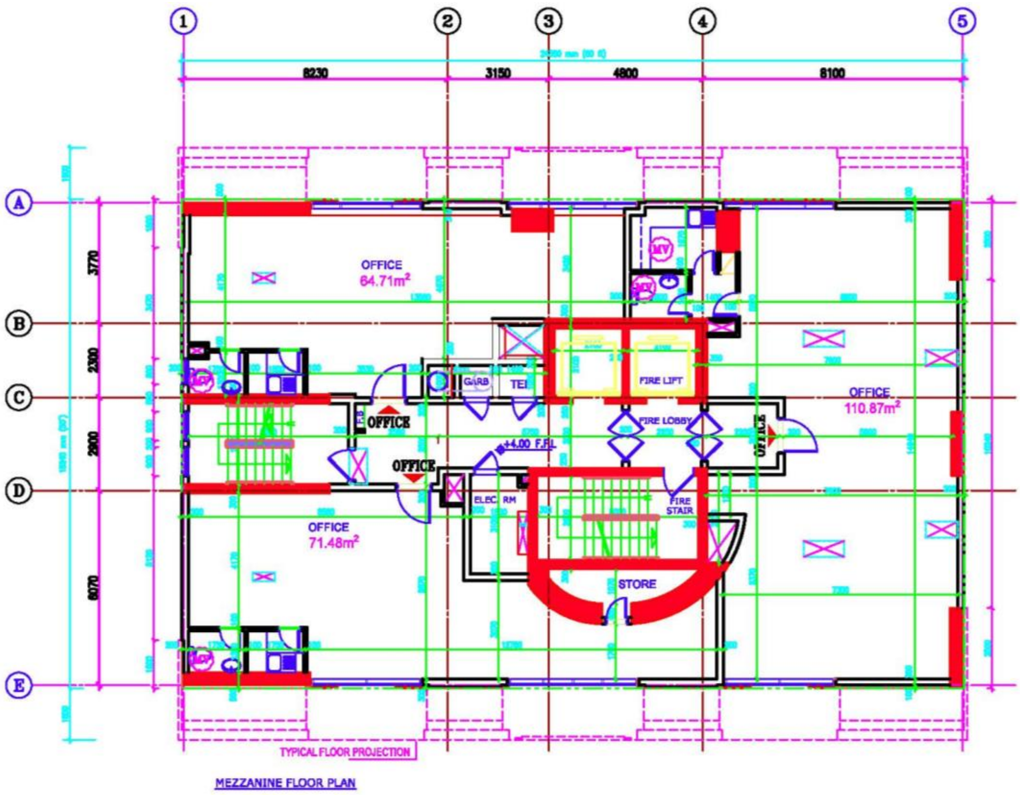


Figure A4. Mezzanine Floor Plan

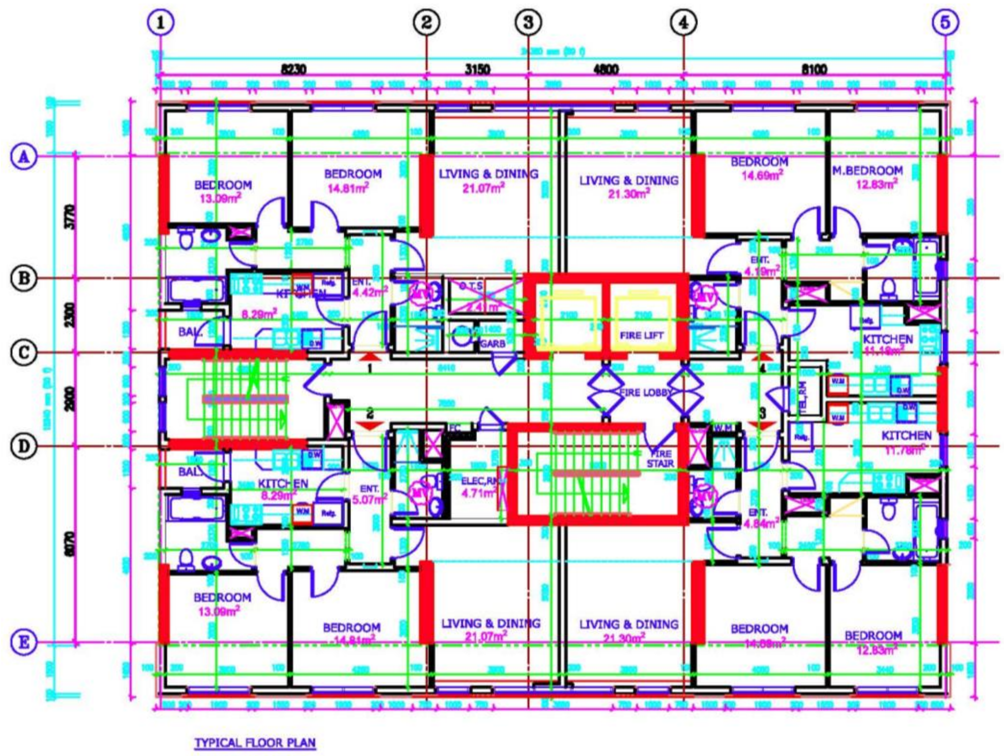


Figure A5. Typical Floor Plan

Element Data:

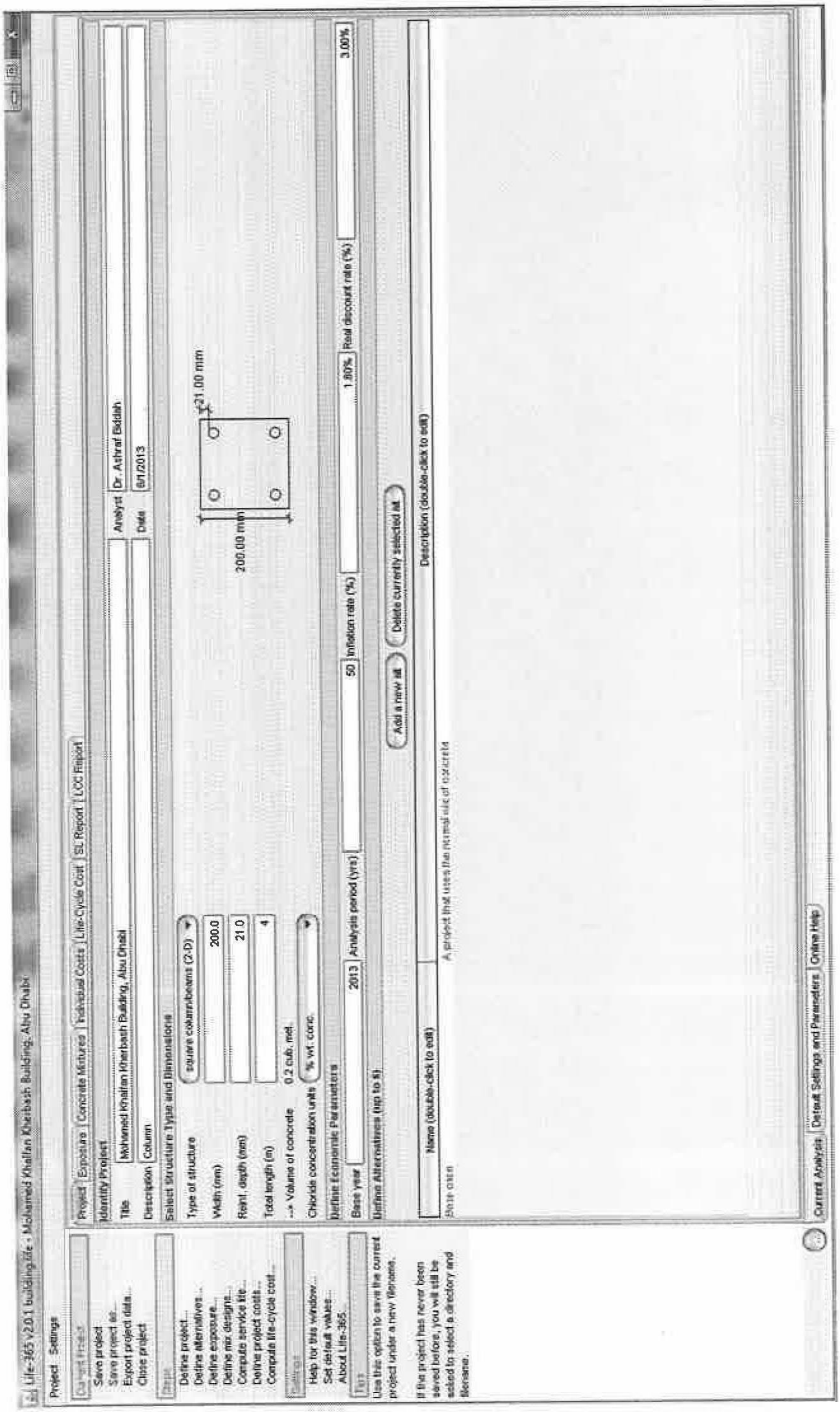
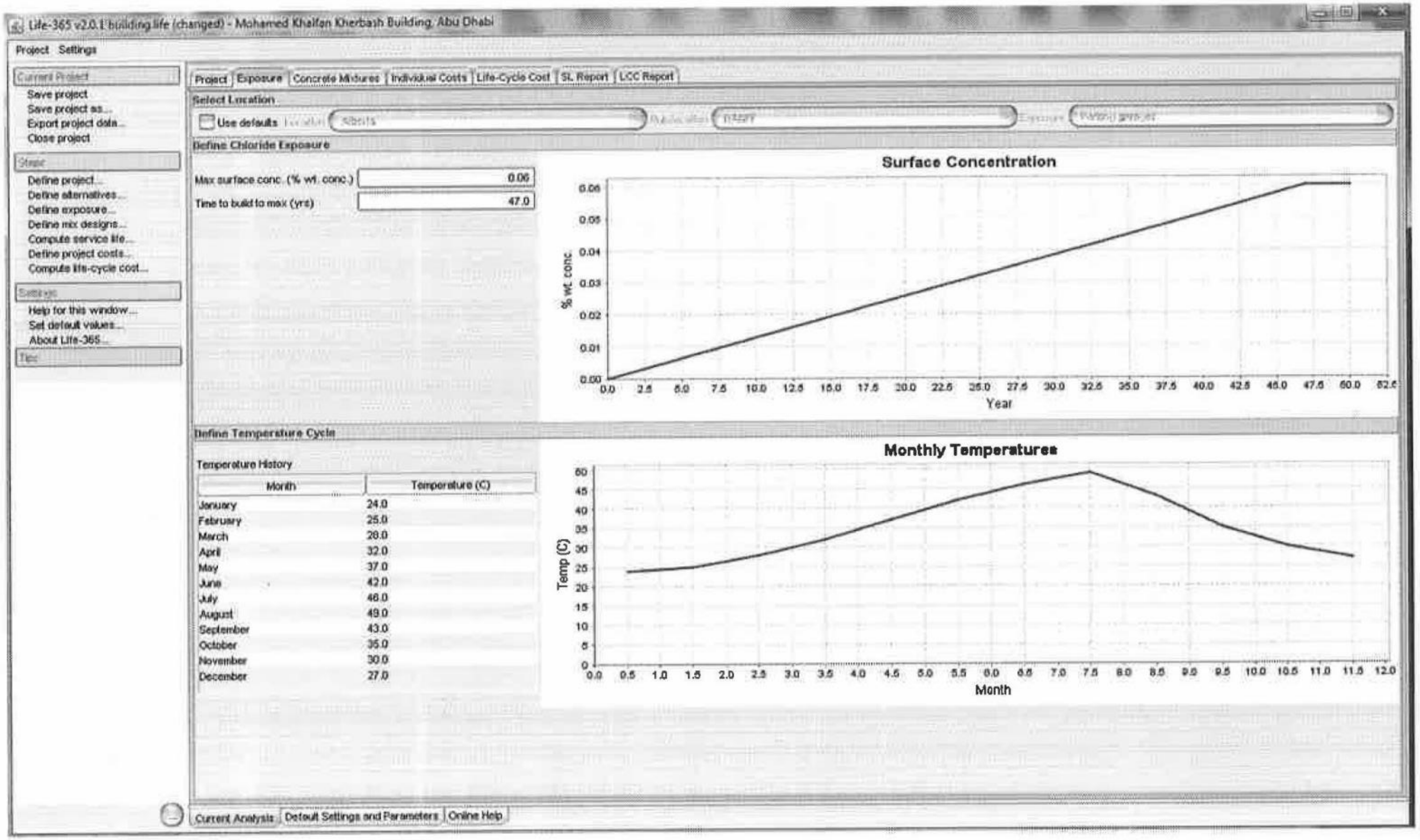


Fig. ED-1

Exposure Data:



Note: The chloride concentration as % of weight of concrete is taken 0.06 after 47 years.

Fig. ED-2

Concrete Mixes and Service Life Results:

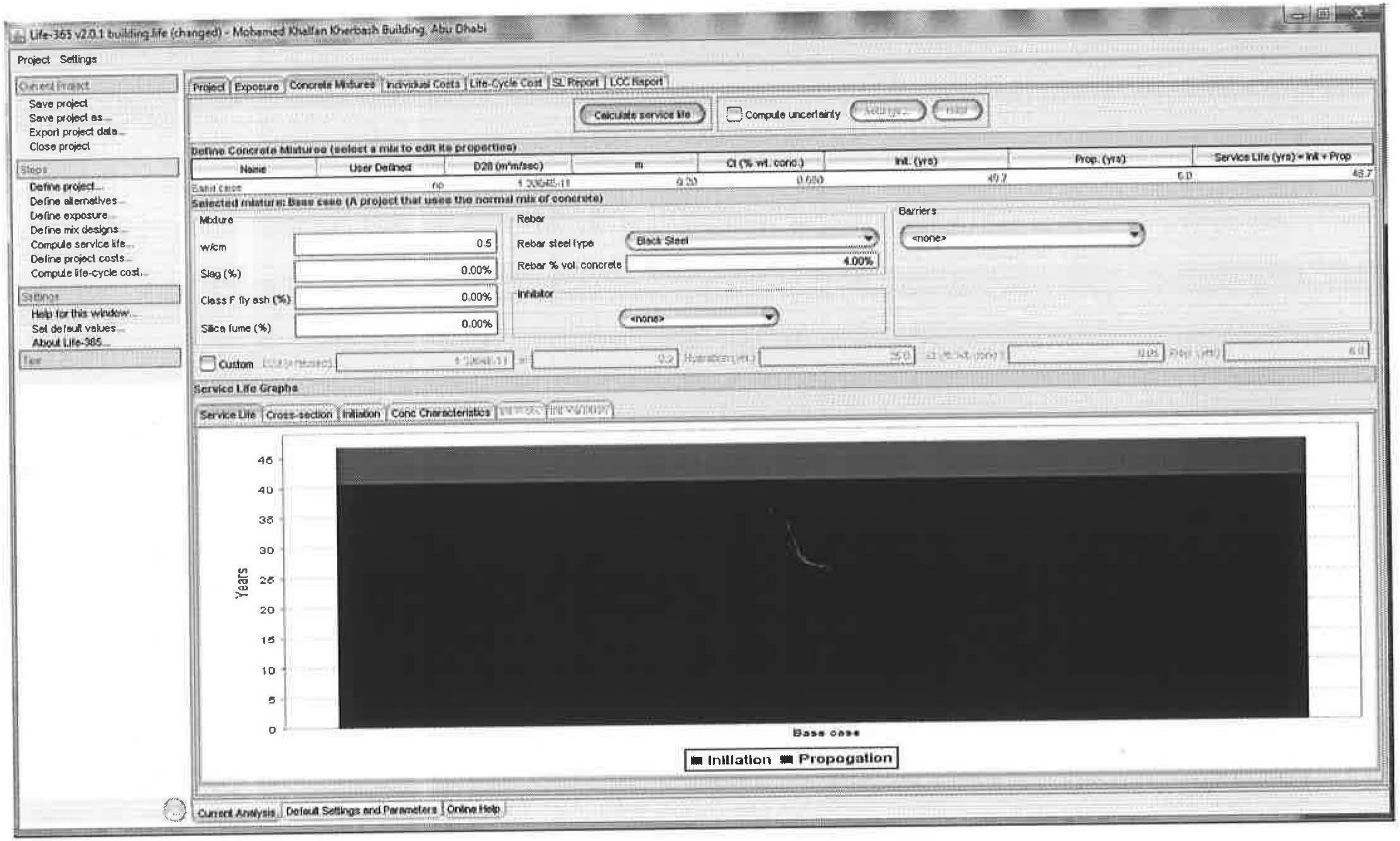


Fig. ED-3

Conclusion of Service Life Analysis:

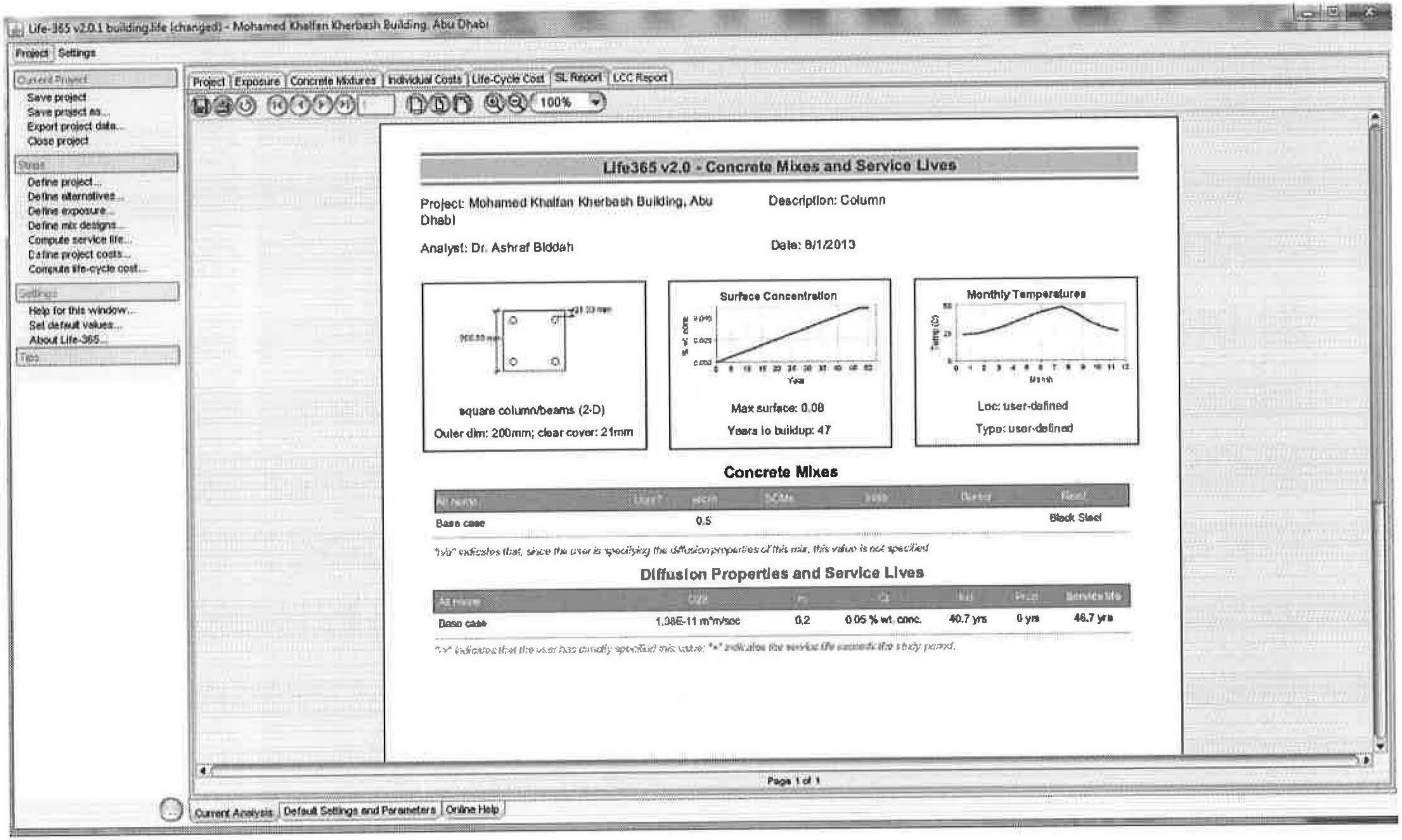


Fig. ED-4

In case of no repair done:

Exposure Data:

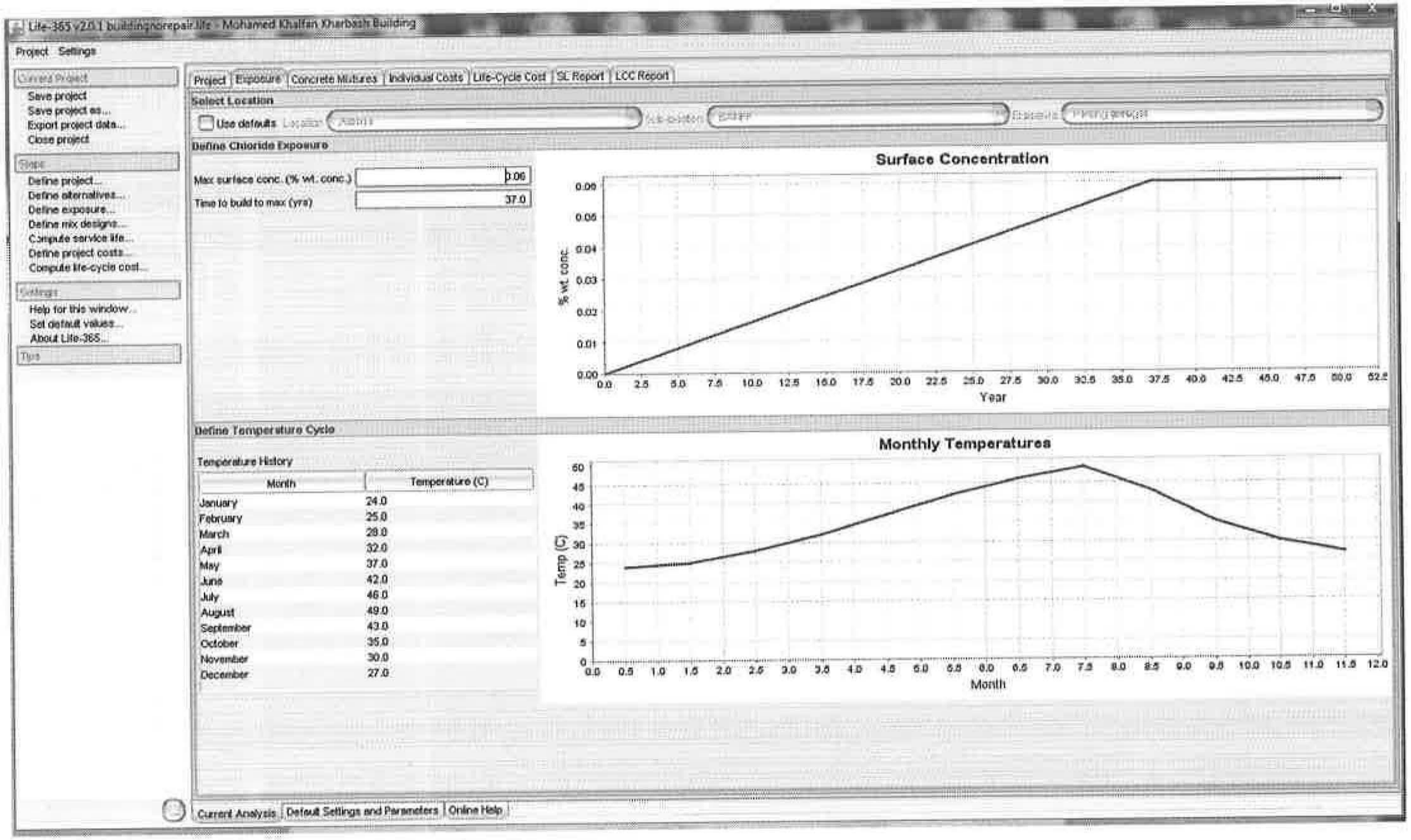


Fig. ED-5

Note: The chloride concentration as % of weight of concrete is taken 0.06 after the real seen initiation of corrosion.

Concrete Mixes and Service Life Results:

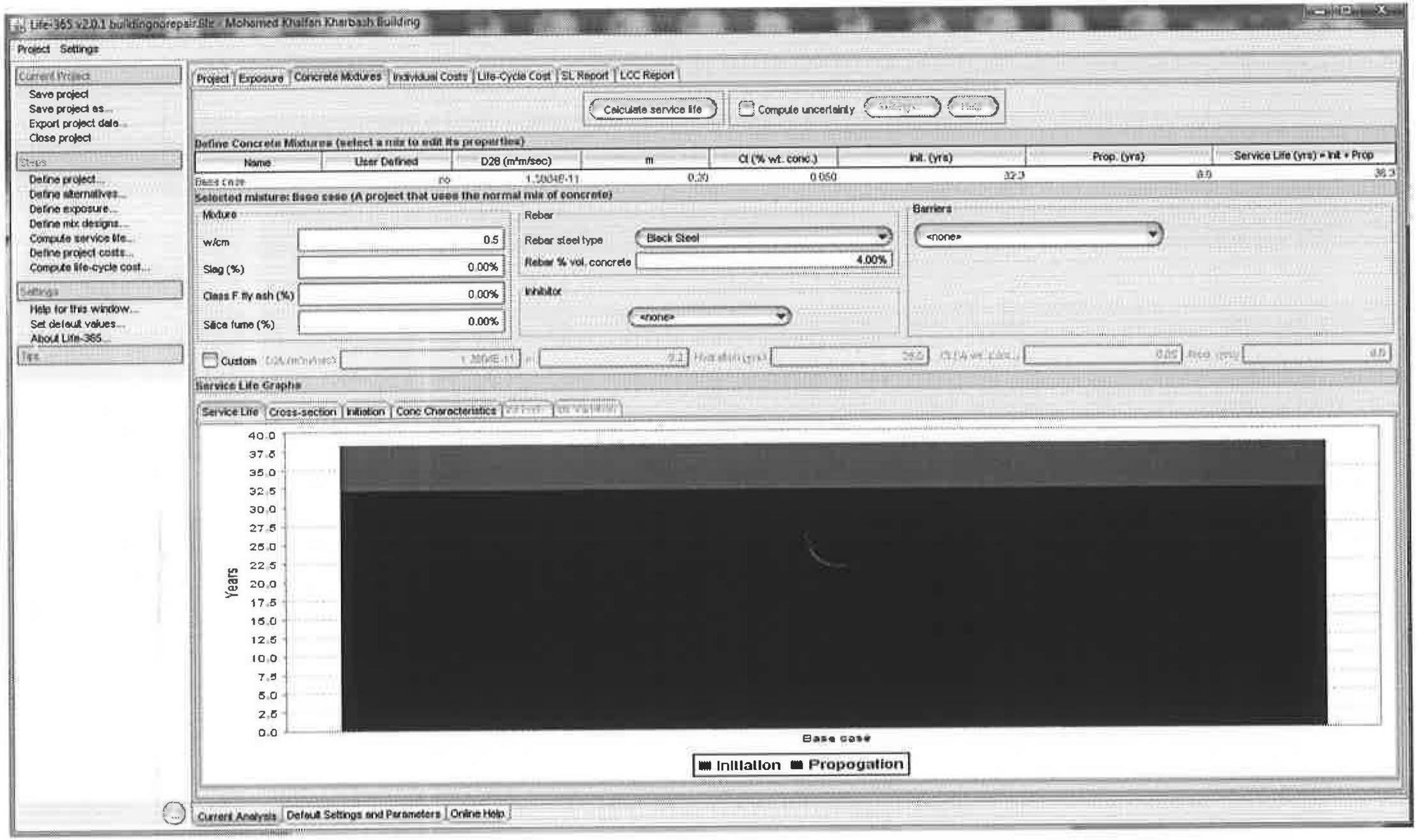


Fig. ED-6

Conclusion of Service Life Analysis:

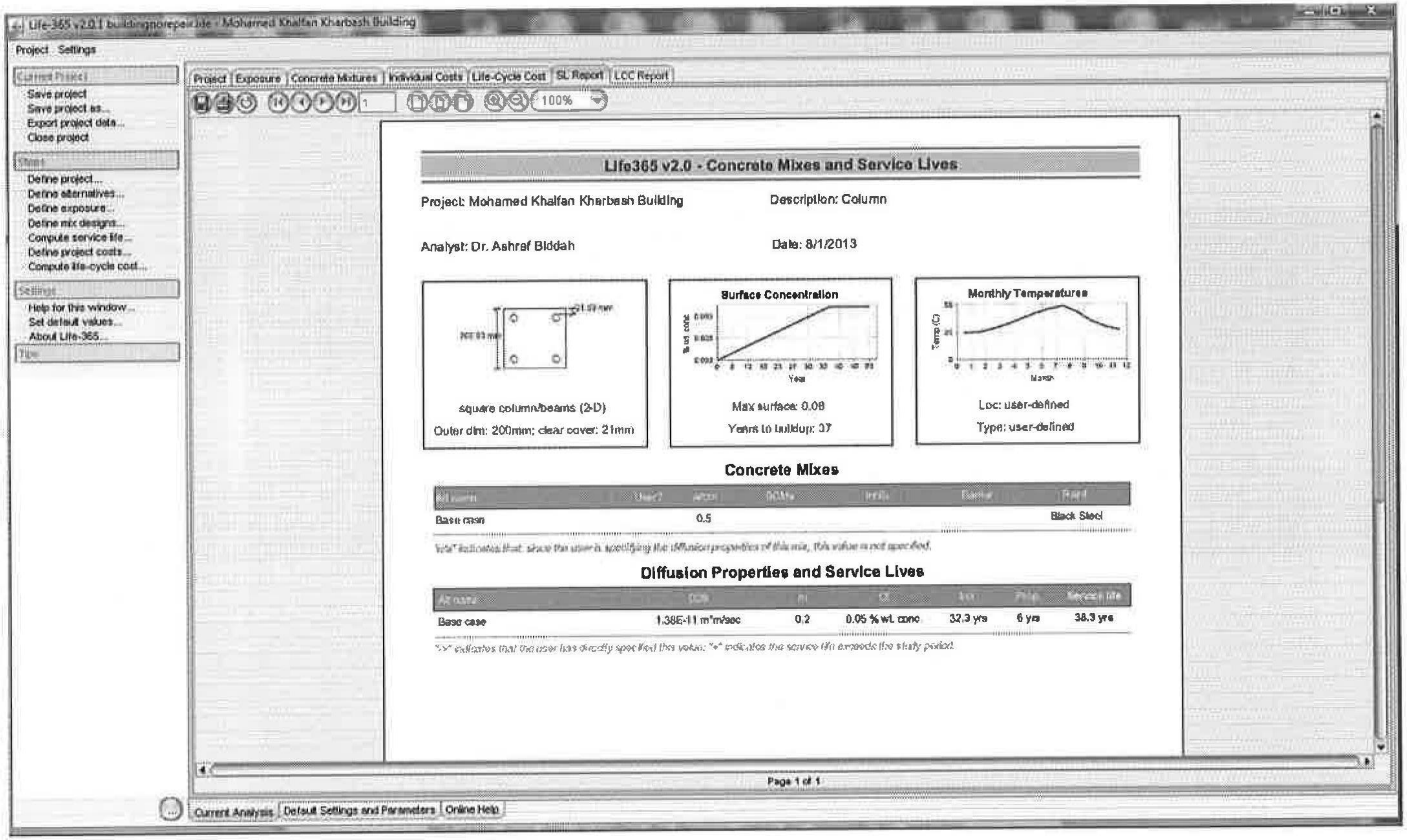
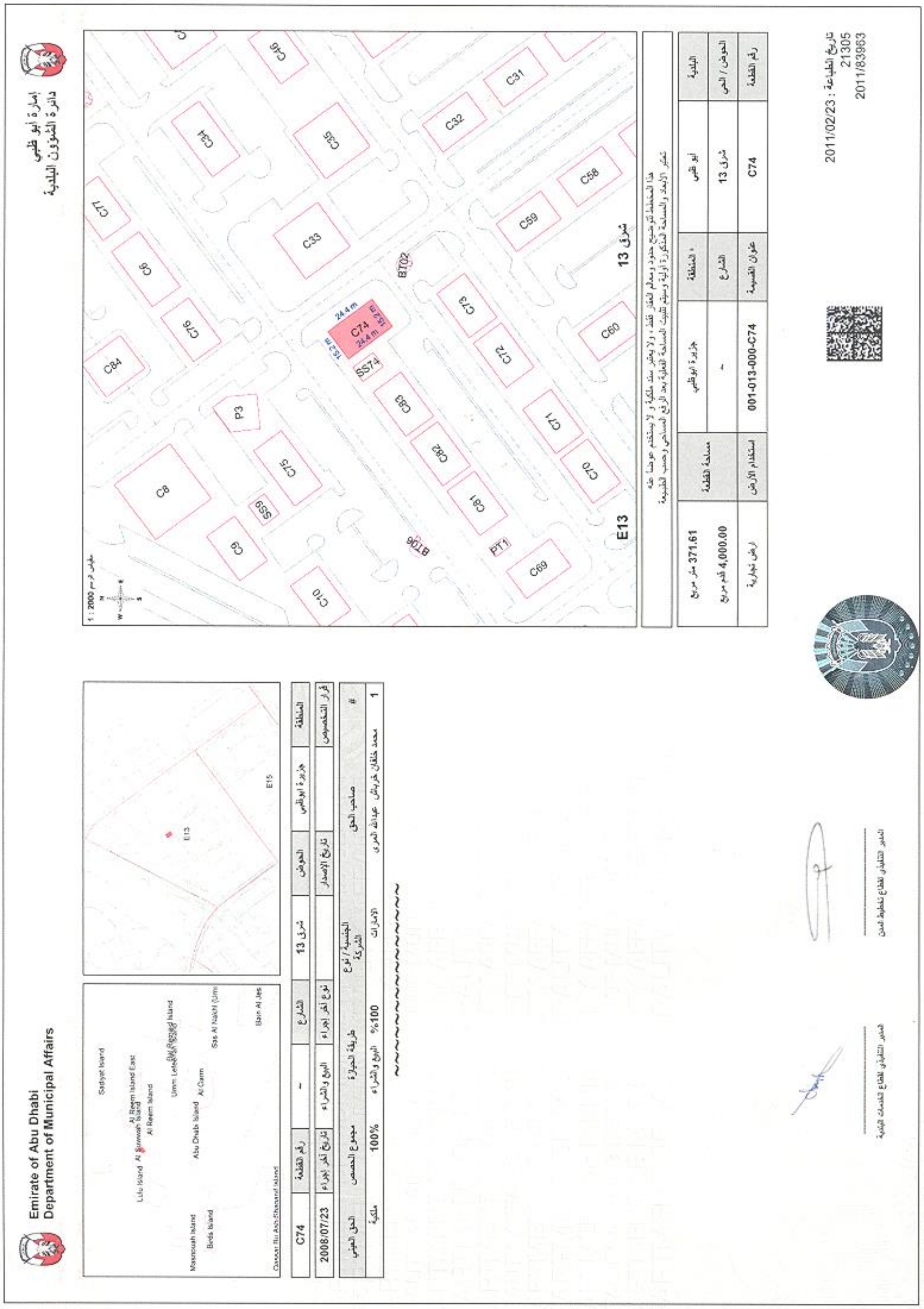


Fig. ED-7

Appendix C: Site Plan of the Plot



Appendix D: Samples of Email Communications

Saturday, October 21, 2017 at 11:06:41 PM Gulf Standard Time

Subject: Re: Request for Information
Date: Monday, February 27, 2017 at 3:40:32 PM Gulf Standard Time
From: Mahmoud Atteya <atteya.mahmoud@ae.sika.com>
To: Golden Planners Consultants <info@gpc.ae>
CC: Eng. Anas Dibsi <a.dibsi@gpc.ae>, Joeman Mosaso <mosaso.joeman@ae.sika.com>

Dear Mr. Anas,

The average market prices including materials and application (1000 DHS/M2)

Best Regards

BUILDING TRUST

Mahmoud Atteya
Target Market Manager - Refurbishment

Sika U.A.E. L.L.C.
Najda Street. First Flight Courier building - 55172 Abu Dhabi
Phone: +971 2 6430364 - Mobile: +971 50 6580355 - Fax: +971 2 6760840
atteya.mahmoud@ae.sika.com - gcc.sika.com

—————————— DISCLAIMER ————————
Any advice is given and any order is accepted subject to our current terms of sale and delivery. Users must always refer to the most recent issue of the local Product Data Sheet for the product concerned, copies of which will be supplied on request.

From: Golden Planners Consultants <info@gpc.ae>
To: Mahmoud Atteya <atteya.mahmoud@ae.sika.com>, "Eng. Anas Dibsi" <a.dibsi@gpc.ae>
Cc: Golden Planners Consultants <contact@gpc.ae>, Joeman Mosaso <mosaso.joeman@ae.sika.com>
Date: 27.02.2017 15:24
Subject: Re: Request for Information

Dear Mr. Mahmoud,

Thank you for your email

Could you please advice further on the micro concrete used in repair in terms of pricing?

This includes Sikacrete-114, Sika MonoTop 438 R, and Sika Microcrete-2000.

Kindly advice

Very best regards

Anas Dibsi
Senior Manager & Partner

Subject: FW: BASF - "Concere Repairs, Protection & Grouts'' / Mortars, Bonding Agents & Injection Resins (email 2)
Date: Tuesday, July 5, 2016 at 1:01:25 PM Gulf Standard Time
From: Moheb Malak <moheb.malak@basf.com>
To: a.dibsi@gpc.ae <a.dibsi@gpc.ae>

Dear Eng. Anas,

Ref. to our meeting and your email, please find attach some data as requested.

In the sane time, we ned to meet after Eid vacation for more details as agreed.

Happy Eid Mr.Dibasi.

>> Stay Connected
Thanks & Regards

Moheb Malak BSc.Civil Eng.
Business Development Manager
Abu Dhabi & Western Region

Phone: +971 2-5512262 Mobile: +971 56 6960084 Fax: +971 2-5506575 E-Mail: moheb.malak@basf.com
Postal Address: BASF Construction Chemicals UAE LLC, SALES_CS - , - Dubai, UAE

150 years
BASF - We create chemistry

From: Ash Raouf [mailto:ash.raouf@basf.com]
Sent: Thursday, June 30, 2016 2:13 AM
To: Moheb Malak <moheb.malak@basf.com>
Subject: Fw: BASF - "Concere Repairs, Protection & Grouts'' / Mortars, Bonding Agents & Injection Resins (email 2)

Hi Moheb,

As requested.

Kind regards,

Ash Raouf
Gulf Specifications Manager / Business Development

Phone: +971 4-8090800 Mobile: +97 1505587253 E-Mail: ash.raouf@basf.com
Postal Address: BASF Construction Chemicals UAE LLC, Sales&Mrkt , Dubai, UAE

150 years
BASF - We create chemistry

----- Forwarded by Ash Raouf/EB-EUROPE/BASF on 06/30/2016 02:12 AM -----