

EFFECT OF PRE-LOADING ON THE CORROSION OF REINFORCEMENT IN RC BEAMS

A thesis report submitted in the partial fulfillment of the

requirements for the award of the degree of

MASTER OF ENGINEERING

IN

STRUCTURAL ENGINEERING

Submitted by

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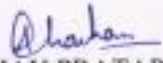
JULY 2015

DECLARATION

I hereby declare that the work presented in this thesis report entitled “**Effect of Pre-loading on the Corrosion of Reinforcement in RC Beams**”, in partial fulfillment of the requirements for the award of the degree of **MASTER OF ENGINEERING in STRUCTURAL ENGINEERING** is an authentic record of the work carried out by me under the supervision of **Dr. Naveen Kwatra, Professor and Head, Department of Civil Engineering** and **Dr. Shruti Sharma, Associate Professor, Department of Civil Engineering, Thapar University, Patiala.**

Further, the matter contained in this report has not been submitted in part or full to any other university or institute for the award of any degree.


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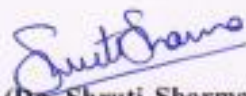

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CERTIFICATE

This is to certify that the above declaration made by the student concerned is correct to the best of my knowledge and belief.


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ABSTRACT

Corrosion in RCC structures is a major durability problem, especially in marine environments. The loading history or the presence of loads, which is the scenario in RC structures in everyday use, has a significant effect on the corrosion process. These loads lead to the formation of micro or macro cracks, which accelerate corrosion and lead to localized failure of the elements.

This experimental study focuses on chloride-induced corrosion of five RC beam specimens of dimensions 150 mm x 150 mm x 700 mm. Reinforcement detailing and concrete mix proportions used are the same for all the beams tested. Beam B1 is the healthy beam which is neither corroded nor subjected to sustained or pre-loads. Beams B2, B3 and B4 have been subjected to 25%, 50% and 75% of the ultimate load capacity of the beam B1 respectively before subjecting them to corrosion. Beam B5 is pre-loaded to 50% before sustained load of 1% is imposed during corrosion. The corrosion process is accelerated using a 20V DC power supply and wet-dry cycles. All the beams are corroded for 15 days.

Results indicate that corrosion is affected by the level of pre-load applied to the beam. In addition, corrosion led to a change in the mode of failure from brittle shear to ductile flexure type in the pre-loaded beams. The amount of corrosion has been measured using gravimetric weight loss. It was found that the load-carrying generally decreased with increasing amount of corrosion of the beams, with exceptions in beams B3 and B5, which are due to the localized nature of corrosion induced by the chlorides and the failure of the gravimetric loss method to include this effect in its formula. Also, the combination of pre-load of 50% with a sustained load of 1% in the case of B5 caused greater loss in the load-carrying capacity than in B3, in which only a pre-load of 50% is applied. This is attributed to the phenomenon of self-healing and reduction in crack-widths upon the removal of loads in the case of B3 which is not subjected to any sustained load while corrosion. Finally, the ultimate strengths of the tensile bars of the beams were found to be decreasing with decreasing load-carrying capacities of the beams.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

Reinforced Concrete Construction (RCC) has been in general use since the last century and is now widely accepted as the preferred choice of construction. Reinforced concrete is a composite material in which steel bars are embedded in concrete in such a way that the two materials, viz. concrete and steel interact with each other to behave structurally as a unit, providing better mechanical properties and high durability in general.

In modern construction practice, a much higher incidence of failures have been found to have occurred in the serviceability state of RC structures as compared with failures in the ultimate state. Particularly, it is the serviceability limit state of *durability* that has become a significant problem. Corrosion of reinforcement has been a major durability concern for new and existing RC structures. In the USA, it is estimated that there is 150 billion dollars worth of corrosion damage in highway bridges due to deicing and sea salt induced corrosion [1]. In the UK, the Department of Transport's estimate of salt-induced corrosion damage is 616.5 million pounds on road bridges in England and Wales alone [1]. In coastal areas of North Africa and in the Middle East (Arabian Gulf), some buildings have been completely destroyed due to corrosion damage [2].

In modern times the corrosion deterioration of RC structures has increased which can be attributed to changes that have taken place in concrete technology and in the environmental conditions in which concrete is being used. Some of these changes are as follows [1][2][3]:

- Up to the 1950's, carbonation was the main cause of corrosion of RC structures. Since then, corrosion caused by chlorides has become the dominant phenomenon. Environmental conditions in many cases have become more severe than those for which the structure was designed in the first place. For example, in cold climates, de-icing of highways by chloride salts is being carried out with more frequency to meet the needs of the increased traffic. This is leading to higher chloride ingress in highway bridges and parking garages in these regions.

- Increased construction of RCC structures in marine environments, where the concentration of chlorides in the environment is higher than usual. Use of sea-water, sea-dredged sand and gravel without washing with chloride-free water has led to a premature failure in many structures, particularly in the marine environments of the Middle-East countries.
- Many buildings constructed in cold climates in the 1960s and 1970s, particularly in Northern Europe, incorporated Calcium Chloride (CaCl_2) in the concrete mix as an accelerating admixture. Typical chloride contents of 0.5-2% by mass of cement in the mix were found to have caused extensive corrosion in these structures. The use of CaCl_2 in concrete mix is now forbidden in construction practice.
- Modern cements are designed to achieve higher levels of strength and obtain most of their strength potential within 28 days. This is done by using higher C_3S (Tricalcium silicate) content and higher fineness, which in turn leads to higher w/c ratios in concrete and less reserve for hydration after 28 days. These factors reduce the effective long-term protection of the concrete cover.
- Sometimes, there is a tendency to reduce the concrete cover depth to improve the structural behavior in RC elements. If in addition to this, there is lack of proper workmanship, then the effectiveness of concrete cover against corrosion is reduced.

1.2 CORROSION OF STEEL IN CONCRETE

The main cause of corrosion of any metal is its thermodynamic instability, as a consequence of which its tendency is to go back to more stable compounds, such as its oxides or hydroxides [4]. The process of corrosion of steel reinforcement in alkaline concrete is quite different from corrosion in natural environment. The concrete surrounding the steel has a high pH value (12-13) [5]. This high pH value prevents corrosion by helping the formation of a very thin passive ferric oxide film, which is a few nanometers thick [5]. This film reduces the metal loss due to corrosion to very small values and corrosion does not pose a significant problem.

This passivating film becomes unstable and is depassivated due to carbonation of concrete or chloride attack. The ingress of harmful species, viz. chlorides, carbon dioxide, oxygen and water is dependent primarily on the quality of the cover concrete. High strength concretes and concretes incorporating pozzolanic materials generally have higher resistance to ingress of these species, as the pores inside the concrete will be more discrete, smaller in size and isolated than

ordinary concretes. This reduces permeability of the concrete and prevents deterioration of steel embedded in the concrete. However, once the oxide film around the bar is depassivated, the reinforcing steel becomes vulnerable to corrosion. Four elements are necessary for the corrosion process to initiate. These elements are given below and shown in **Figure 1.1**.

- Anode- location where corrosion of steel takes place and from where electric current flows.
- Cathode- location where no corrosion occurs and to where electric current flows.
- Electrolyte- medium which facilitates the movement of ionic current. In concrete, the pore water solution acts as the electrolyte.
- Metallic path- Connects the anode and the cathode, and completes the electric circuit. Steel provides the metallic path in reinforced concrete.

The basic reaction at anode is [1]:



The electrons released at the anode are consumed by cathode by reduction process. The most probable reaction at cathode (provided O_2 is available and pH is sufficiently low) is [1]:

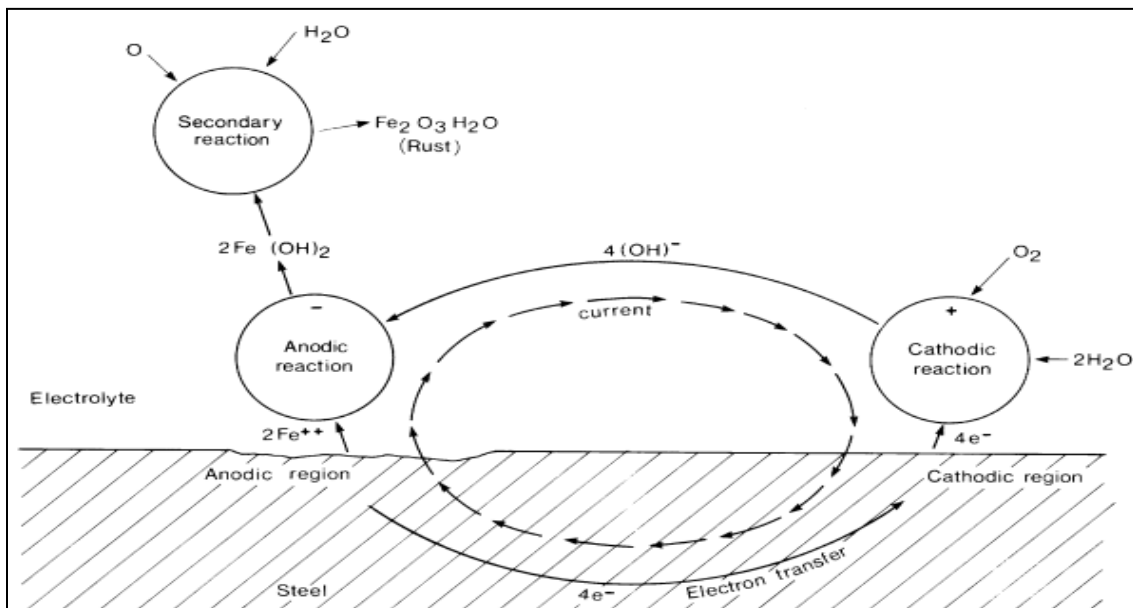
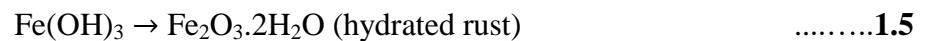
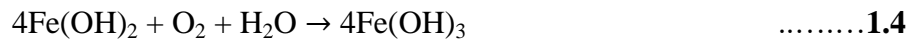


Figure 1.1: Anodic and cathodic reactions and products of the corrosion process [6]

Both anodic and cathodic reactions are required to occur simultaneously for corrosion to occur. The complete reaction gives the following equation [1]:



If water and oxygen are present in the concrete pore solution, ferrous hydroxide further reacts to give Fe_2O_3 [1]:



These rust products may get accumulated on the surface of the steel, or they may get washed away in the presence of flowing water. The former case is more harmful, as hydrated rust products at concrete/steel interface may have six to ten times more volume than the parent steel [1]. Due to this volume increase, they exert outward pressures on the surrounding concrete, which, owing to its low tensile strength, cracks easily. This may lead to an acceleration of the corrosion process. Also, in the former case, there may be no prior warning of corrosion process going on, whereas in the latter case, due to the reddish brown color of the rust stains left on the concrete surface, one may perceive that corrosion process is underway, and take appropriate measures to handle the situation. Also, if at anode, there is a low concentration of oxygen, the type of rust produced is black/green in color, which usually occurs in cases of buildings immersed in water or when a protective layer prevents the presence of oxygen. This type of corrosion is critical because it does not give any warning by way of cracks or spalling of cover concrete [2].

In practical situations, engineers are primarily concerned with whether or not there are sufficient concentrations of carbon dioxide or chlorides, oxygen and water to break down the passivating film and initiate corrosion. If initiated, the resulting rate of corrosion and its effect on the service life are important parameters of study.

1.2.1 TYPES OF CORROSION

There are two basic types of corrosion that are commonly responsible for deterioration of a RC structure. These are as follows:

- **Carbonation-induced corrosion:** In humid environments, carbon dioxide present in the atmosphere forms an acid aqueous solution which can react with the hydrated cement paste, and subsequently reduces the pH value of the alkaline pore solution from about 13 to 9 [5]. The reaction starts at the external surface and penetrates into the concrete producing a low pH front. The rate of penetration depends on environmental factors (humidity, temperature, concentration of carbon dioxide) and the properties of the concrete (alkalinity and permeability). Once the carbonation front reaches the embedded reinforcement, steel is depassivated and corrosion can occur if oxygen and water are present in sufficient quantities. This type of corrosion generally leads to a uniform corrosion of the reinforcement.
- **Chloride-induced corrosion:** In RC structures located in coastal zones and in cold climates where de-icing salts are used extensively, corrosion caused by the penetration of chloride ions is the most important mechanism responsible for degradation. The ingress of chloride ions from the environment to the level of reinforcement depends upon the quality of concrete cover. The accumulation of the chloride ions at the level of reinforcement beyond a certain amount (critical chloride content) will initiate corrosion in the presence of water and oxygen. This type of corrosion leads to localized ‘pit’ formations in the reinforcement. In these pits, corrosion is accelerated by a great extent and can reach very high rates of penetration (up to 1 mm/year) [5]. The highly localized reduction of the cross-sectional area of steel reinforcement is much more than that encountered in the case of carbonation-induced corrosion.

1.3 EFFECT OF CORROSION ON STRUCTURAL BEHAVIOR OF RC ELEMENTS

Corrosion of steel in concrete may cause deterioration of safety and performance aspects of RC elements of the structure. It may affect the mechanical properties of the structures in the following ways:

- Reduced load-bearing capacity due to loss of cross-sectional area of rebar.
- Reduced load-bearing capacity due to bond weakening at the concrete-steel interface.
- Loss in ductility due to variations in cross-sectional areas of the rebar and stress concentrations due to abrupt changes in geometry of rebar.

- Formation of cracks along the length of rebar due to excess tensile stresses exerted by the corrosion products on the surrounding concrete. In some cases, delamination and spalling of cover concrete may also occur.
- Corrosion may change the failure mode of RC elements, and in case of under-reinforced sections may lead to a brittle failure with little or no warning of the impending failure.

1.3.1 EFFECT OF CORROSION ON SERVICE LIFE OF RC STRUCTURES

Service life of a structure may be defined as the time for which a structure is expected to be able to fulfill its requirements with sufficient reliability with or without periodic inspection and maintenance and without unexpected high costs of maintenance and repair [4]. The service life of a RCC structure with respect to corrosion is generally described in terms of two phases of corrosion process - initiation and propagation phases as shown in **Figure 1.2**. It can be seen that once the corrosion has initiated, the remaining service life will depend upon the rate of corrosion. If the rate is high, the slope of the straight line is steeper, thus reducing the service life of the structure.

Corrosion initiation period defines the time required by the chloride ions or carbon dioxide (harmful species) to penetrate through the concrete cover and accumulate at the level of steel reinforcement in such an amount that the passive layer surrounding steel surface is depassivated and corrosion process has effectively begun. In the absence of cracks, the initiation phase generally depends upon the permeability of cover concrete, type of binder and the corrosion resistance of the steel bars. But in the presence of cracks, only the bar resistance to corrosion may be of practical significance.

Corrosion propagation phase is the period during which the corrosion rate and the amount of corrosion products gradually increase until the level of deterioration becomes unacceptably high. The slope of the graph may become progressively steeper in the presence of cracks, as the corrosion process may lead to cracks, allowing easier penetration of the harmful species. Increased concentrations of these species may lead to increase in the rate of corrosion, leading to further wider corrosion cracks, which may further still accelerate corrosion deterioration. Therefore, presence of cracks may affect the service life more profoundly.

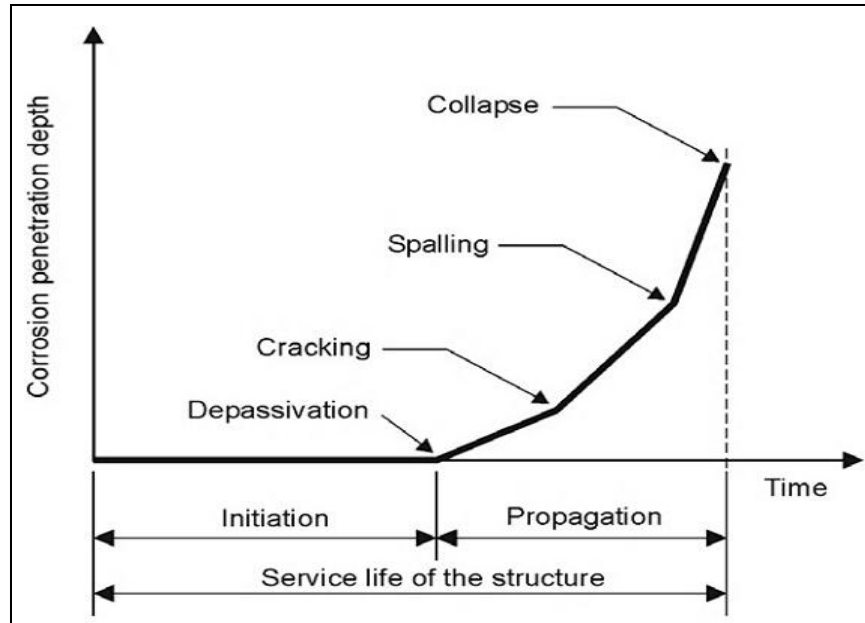


Figure 1.2: Modified Tuutti Corrosion damage model [5]

1.4 EFFECTS OF PRE-LOADING ON CORROSION

The use of limit states design method and higher grades of concrete and steel in modern RC construction has led to overall thinner member sections and higher stress levels at service loads. This has resulted in greater deflections and crack-widths in these structures as compared to the earlier structures designed by the more conservative working stress method and using mild steel and lower concrete grades [8]. Consideration of cracking is therefore necessary in a realistic assessment of corrosion process in RC structures.

A large number of experimental and analytical studies have been carried out in order to gain understanding of the effect of corrosion process on the structural behavior of RCC elements, especially beams and slabs. Majority of these investigations have been performed in the laboratory environment as a two stage process i.e., the 'unloaded' RC member is first corroded to a desired level and then loaded to test the residual properties. However, many existing RC structures in service may be cracked. This may occur, for example if the functional use of the building is altered. Also, there may be occasional overloading of the structure, which may cause cracking of cover concrete of RC elements. Cracks may be present in RC structures even under the normal range of service loads or due to effects of creep, shrinkage or settlement at supports. Pre-loading can cause cracking in the member, and may alter its behavior more significantly,

leading to a greater loss of ultimate strength, ductility, and rate of corrosion than in the case of corrosion of unloaded (uncracked) members. The behavior may be further altered if a sustained load is applied to the cracked member.

Two types of cracks may affect the behavior of a RC structure undergoing corrosion - those present before the onset of corrosion which may assist the corrosion process, and those which are produced as a direct consequence of corrosion. The present study is interested in the former type of cracks.

The presence of cracks in a RC member may affect its structural behavior and also may adversely affect its durability by providing easy access to aggressive agents, especially chloride ions in marine environments. Presence of cracks in concrete may cause localized chloride ingress and hence localized corrosion of steel reinforcement. Further, crack-widths, crack frequency and orientation may also affect the corrosion process. Some of these effects may be reduced by the phenomenon of *autogenous or self healing* of cracks having relatively smaller crack-widths (<0.5 mm), which involves swelling and hydration of cement paste and subsequent precipitation of calcium carbonate crystals in the cracked zone, and which leads to reduction in penetrability of harmful species, thereby improving the reinforcement protection from corrosion [9].

1.5 OBJECTIVES OF THE STUDY

The main objective of the present study is to investigate the effects of accelerated corrosion under varying levels of pre-loads on the ultimate strength, amount of corrosion, and modes of failure of the RC beams. Although the effect of sustained loads was another main objective of the study, due to lack of appropriate loading mechanism more detailed investigation into its effects was not carried out.

1.6 SCOPE OF THE WORK

The main parameter of the present study is the pre-load level applied on the beam specimens. The scope of work involved is described as follows:

- Five RC beams of dimensions 150 x 150 x 700 mm, using M25 and Fe500D grades of concrete and steel respectively are cast. After curing for 28 days, the uncorroded healthy beam is tested in four-point loading and its ultimate load capacity noted.

- Three beams are subjected to pre-load values of 25%, 50% and 75% of the observed ultimate load capacity of the uncorroded beam and then corroded by impressing a constant voltage of 20 V.
- One beam which is pre-loaded to 50% of the ultimate load of the uncorroded beam is subjected to a 1% sustained load whilst corrosion.
- After corroding for 15 days, these beams are tested to failure and their load-deflection curves are plotted. Also, modes of failure of these beams are observed. Comparison of beams is made with respect to load-deflection and ductility characteristics. Amount of corrosion is determined by using the gravimetric mass loss technique. Finally, reduction in the ultimate strength values for the tensile bars is reported.

1.7 THESIS LAYOUT

This thesis is divided into five chapters. They are briefly summarized below:

Chapter 1: Describes in general the corrosion process and its effects on structural behavior of RC members. Also, the objectives of the study are enumerated.

Chapter 2: Presents the available literature review of previous research relevant to the topic of study, i.e. effects of pre-loading and sustained loading on reinforcement corrosion.

Chapter 3: This chapter explains in detail the materials used and the experimental process employed in the study.

Chapter 4: In this chapter, results of the experimental study are presented and discussed. Finally, conclusions based on the study are drawn and the direction for further work is suggested.

Chapter 5: Presents the conclusions drawn from the study and also the scope for future work related to the present topic of investigation.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

A large amount of literature exists regarding corrosion of RCC elements in concrete structures. Including all fields of research related to this topic would be an immense task. However, as the present study is related to corrosion of reinforcement in beams subjected to pre-loads, it would be appropriate to include some important research work done involving corrosion of RC beams subjected to static loading either before or during corrosion, i.e. under sustained loads or pre-loads or both. Also, work done by researchers on RC beams on corrosion without applied loads has also been reported. Finally, some of the commonly methods for accelerating corrosion have been explained.

It was observed during review of the available literature that most of the work related to corrosion of RC beams under loads has been done in the presence of sustained loads, while only a few researchers included pre-loading as a parameter of study, and only one research paper described the combined effects of pre-loading and sustained loading on the structural behavior.

2.2 CORROSION UNDER PRE-LOADS

Uomoto and Misra (1988) studied on the effects of longitudinal cracking (due to corrosion) on RC beams and columns. They tested two series A and B of 4 beams each. In series A beams, dimensions of 100 mm x 100 mm x 700 mm were used with tension reinforcements of diameters 6, 10, 16 and 19 mm ribbed bars. Concrete covers of 10 and 20 mm were used. Sodium chloride contents of 0, 0.5 and 3.3% were added to the mixing water. Some of the beams in this series were loaded to induce flexure cracks, after which an impressed current of 167 mA was applied for 10 days.

Series B beams had dimensions of 100 mm x 200 mm x 2100 mm with two 16 mm diameter tensile bars, two 6 mm diameter bars in compression zone and 6 mm stirrups at 170 mm spacing. 1.25 kg/m³ sodium chloride by weight of concrete was added to the mix. After moist curing in

air for 2-4 weeks, a current of 1 A was impressed on the bars for 7, 14 and 14 days to accelerate corrosion

For beams in series A, it was found that the corroded specimens without induced flexural cracks had residual load-carrying capacities of around 95, 92 and 66% for 0, 0.5 and 3.3% NaCl respectively, whereas for beams with induced flexural cracks the values were 90, 81 and 76% respectively. Also, while the control beam and beam corroded with 0% NaCl failed in flexure, other (more corroded) beams failed in shear-bond.

For the series B beams, corrosion in the corroded beams was found to be 1, 1.2 and 1.4% for 7, 14 and 14 days corrosion respectively. The load-carrying capacities for these beams were 96, 92 and 83% respectively for increasing corrosion. The load-deflection curves for 0 and 1% corroded beams exhibited distinct yield points and plateaus, while 1.2 and 1.4% corroded beams failure was abrupt with no plateaus after peak. The failure of corroded beams occurred under flexure in combination with spalling of concrete and buckling of reinforcement in compression zone [10]

Huang and Yang (1997) carried out an experimental study to determine the relationship between the corrosion level of reinforcement in RC beams and their load-carrying capacity. For this, beam specimens of dimensions 150 mm x 150 mm x 500 mm were used. The beams were reinforced with two 6 mm diameter bars in the tensile zone. The beams were of two types- beams without cracks (S), and beams with a middle surface crack (K). In addition, two types of concrete mixes were used- one having a water/cement ratio of 0.4 (A) and the other with a ratio of 0.3 (B). Therefore, there were four combinations of beam types- AS, AK and BS, BK. The beams were immersed in sea-water and a constant current density of 5 A/cm² was applied to corrode the RC beams.

It was found that with the increase in corrosion of reinforcement, the load-carrying capacity of the beams also reduced. The reduction was found to be greater in beams which had a low w/c ratio (0.3) or which were pre-cracked, as shown in **Figure 2.1** The authors concluded that this was due to the chloride ions having easier access to reinforcements in case of the pre-cracked beams. Also, to explain the fact that lower w/c ratio showed lesser ultimate load-carrying capacity, the authors reasoned that as the beams with lower w/c ratio have smaller pore sizes,

they have lesser energy absorbing capacity (even though they have greater stiffness), and consequently, once cracked, they may fail before the beams with a higher w/c ratio. [11]

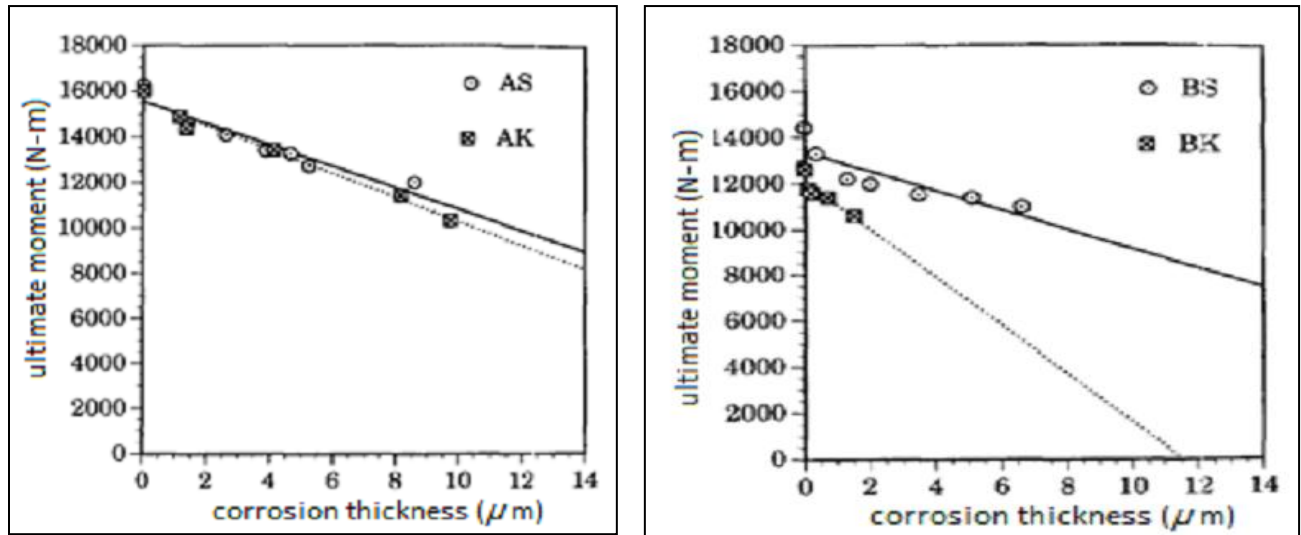


Figure 2.1: Effect of corrosion and w/c ratio on load-carrying capacity [11]

Yoon et al. (2000) performed tests on RC beam specimens of dimensions 100 mm x 150 mm x 1170 mm. The beams were tested under three conditions of loading: under a sustained load, in absence of sustained load but with pre-loading, and in absence of a sustained load with no pre-loading. The loading was applied by a mechanical loading frame as shown in **Figure 2.2**, in such a way that the tensile face of the beam was at top. This was done to monitor the crack propagation easily. A plastic dam containing 5% NaCl solution was built at the top face.

The specimens were tested under four point loading with span length of 1050 mm and constant bending moment region of 230 mm in the middle part of beams. The levels of the sustained loads were kept at 0%, 20%, 45%, 60% and 75% of the ultimate load capacity of the virgin beam. The specimens subjected to 0%, 45% and 75% sustained loads and those subjected to previous loads were tested at both the corrosion initiation and propagation stages. The remaining specimens were only tested at the corrosion propagation stage. In the initiation stage, beams were subjected to four days wetting with 5% NaCl solution and three days drying. Half-Cell potential measurements were used to monitor corrosion initiation. Deflections at mid-span were continuously measured during the test.

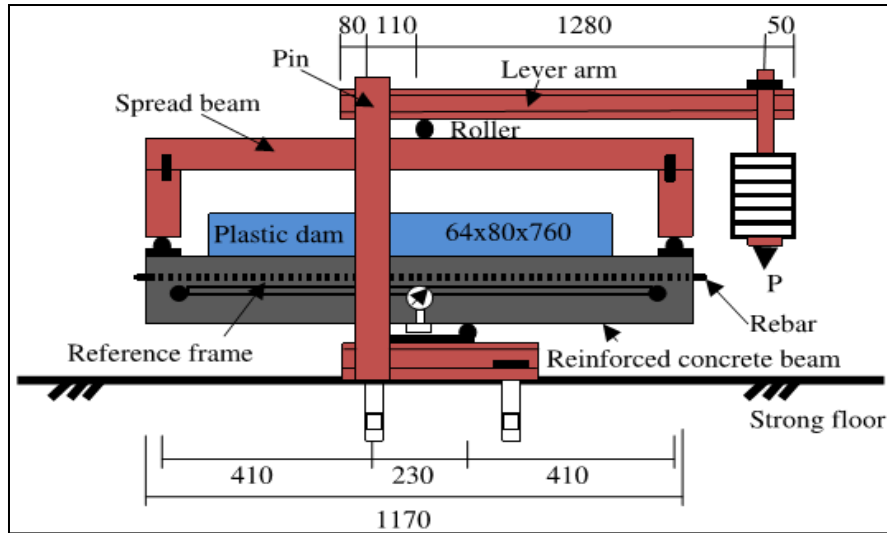


Figure 2.2: Sustained Loading setup (dimensions in mm) [12]

The results showed that beams pre-loaded to high loads had shorter corrosion initiation periods (2 days and 4 days for beams pre-loaded to 75% and 45% of ultimate load respectively). Also, the beams with high sustained loads had shorter initiation periods. (3 days, 10 days and >30 days for beams tested under 75%, 45% and 0% loads respectively). Also, during the initiation stage, deflections increased with a decreasing rate (due to creep effects), with the beams with higher loads showing increased initial and long-term deflections. During the propagation stage, constant voltage was applied on the bars to accelerate the corrosion process. It was found that deflections increased suddenly at application of voltage and then reached a constant value after a certain level of corrosion. The authors attributed the increased deflections to stiffness reduction due to concrete cover cracking.

The rate of corrosion was measured by Faraday's law. It was found that higher rates of corrosion were present in beams subjected to high levels of sustained loads and pre-loads. Also, mass loss of steel was found to be higher in the case of beam tested under sustained load than that of the beam pre-loaded and then corroded under no sustained load. This was attributed to larger crack widths in the beams that were corroded under sustained loads. [12]

2.3 CORROSION UNDER SUSTAINED LOADS

François and Arliguie (1998) performed tests on RC beams kept under sustained loading and simultaneously subjected to corrosion in a confined salt fog environment for a period of 12 years

to simulate actual field conditions for corrosion. Beams of dimensions of 150 mm x 280 mm x 3000 mm were cast. The beams were of two types- type A, which had two 16 mm bars as tension reinforcement, two 8 mm bars as compression reinforcement with 8 mm stirrups spaced at 220 mm, and type B, which had two 12 mm bars as tension reinforcement, two 6 mm bars as compression reinforcement with 6 mm stirrups also spaced at 220 mm. The concrete cover to stirrups was kept as 40 mm for type A and 10 mm for type B beams.

Three-point loading was applied to the beams, which were coupled in a “back-to-front” manner, as shown in **Figure 2.3**. Two sustained load levels, first corresponding to a service moment of 13.2 kN.m (M1) and the second corresponding to 21.2 kN.m (M2) were applied to the beams. According to the French standards, load M1 corresponded to the maximum loading for durability in aggressive environment for type A beam and to maximum loading for resistance in non-aggressive environment for type B beam, whereas, load M2 corresponded to 80% of the failure load (twice the design service load in aggressive environment) for type B beams and to maximum loading for resistance for type A beams. A 3.5% NaCl Salt fog with wetting-drying cycles of 15 days each was used to accelerate corrosion.

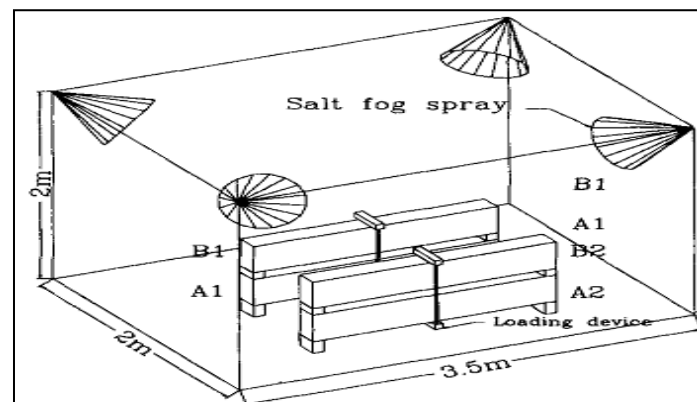


Figure 2.3: Loading arrangement and exposure conditions [13]

Damage was assessed in terms of cracking maps for each beam at three stages- initial state (before sustained loading), after loading (before exposure to aggressive environment) and after exposure to aggressive environment. After exposure to aggressive environment, four beams were mapped for cracking and then were removed from the test chamber after 5 years of exposure and tested for chloride penetration, bending, steel corrosion map and studies of concrete microstructure and steel -concrete interface. Another group of four beams were

similarly mapped for cracks and then tested. The remaining four beams were kept under load and mapped for cracks at 7, 11 and 12 years after exposure.

The results showed that sustained load has an important role in the penetration of aggressive agents and subsequent corrosion of reinforcement. When the concrete cover is small (type B beams), depassivation of steel surface is achieved quicker and also the penetration of chlorides is faster. Also it was found that the secondary cracks due to corrosion of reinforcement were randomly located and depended on various parameters. It was suggested to use a probabilistic approach to obtain accurate modeling of corrosion development. [13]

Ballim et al. (2003) tested RC beams of dimensions 100 mm x 160 mm x 1550 mm under sustained loads. The span was 1050 mm in four point loading with a constant bending moment region of 350 mm in the middle part of the beams. The beams were reinforced with a single 16 mm ribbed bar in the tensile zone, two 8 mm mild steel plain bars in the compression zone and 8 mm plain stirrups at 60 mm spacing in the shear span. The cover to tension rebar was 32 mm.

Sustained load levels of 23% (series 1) and 34% (series 2) of the ultimate load capacity of the control beam were applied on the beams using a compressed spring, which transferred the loads to the beams via a load distributor beam. Before corrosion, the tensile steel was depassivated by carbonation of the concrete up to the depth of tensile bar. The time to depassivation of reinforcement was found to be approximately 6 weeks. The bottom supports and tensile regions of the beams were immersed inside a tank containing 3% NaCl solution. Corrosion of tensile bars was accelerated by applying an impressed current of 300 mA for about 30 days. After completion of corrosion, beams were removed from load rigs and corrosion crack maps were prepared. Deflections at mid- point of beams were measured, and after testing, the corroded bars were taken out of the beams, cleaned, and weighed to determine the gravimetric mass loss.

It was found by the authors that beams corroded under high loads had larger deflections. **Figure 2.4** shows the results for the two series of beam expressed as deflection ratios vs. percent corrosion calculated by Faraday's law. It can be seen that for the same percentage of corrosion, the deflection ratio increased with increase in the sustained load values. For the corrosion crack maps, it was found that while the crack maps were similar for both sustained load levels, beams corroded under higher load exhibited wider cracks.

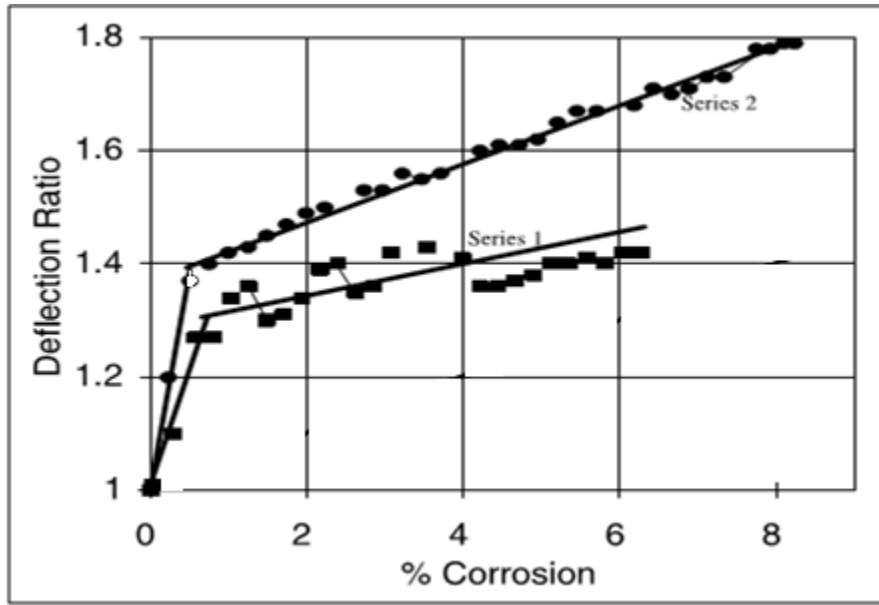


Figure 2.4: Extent of corrosion vs. deflection ratio plots for the two beam series [14]

Furthermore, the gravimetric mass loss of steel bars was found to be consistently lower than the mass loss predicted by Faraday's law. To account for this, the authors concluded that since the load rig was in contact with the NaCl solution, some of the applied current was lost to the corrosion of the frame. [14]

Maaddawy et al. (2005) carried out experiments involving corrosion of eight RC beams of dimensions 152 mm x 254 mm x 3200 mm. The beams were reinforced with two #15 deformed steel bars (16 mm nominal diameter) in tension zone, two 8 mm diameter plain bars in the compression zone, and 8 mm plain stirrups spaced at 80 mm in the shear span and 333 mm in the constant moment region. The clear cover to stirrups was 25 mm. To achieve corrosion of only the tensile reinforcements, the middle eight stirrups in each beam were coated with an epoxy resin to protect them from corrosion. Corrosion was restricted to the tensile reinforcement placed in the middle 1400 mm of the specimens. To depassivate the tensile reinforcement, 2.25% Cl⁻ ions (by mass of cement) were added to the cement in this middle 1400 mm region to a height of about 100 mm from the bottom face of the specimens. The tensile bars were extended about 76 mm out of one end to allow electric current to be applied to the specimens. Water/cement ratio of 0.55 was used in the experiment. Maximum aggregate size of 13 mm was used in the concrete mix.

A total of nine beams were used in the experiment. The beams were divided into two groups- A and B. The four beams in group A were corroded for periods of 50, 110, 210 and 310 days without any sustained load, while the four beams in group B were corroded for the same periods but under a sustained load equivalent to 60% of the ultimate moment of the control beam. The sustained loads were applied by using a mechanical frame. The frame applied load on two beams simultaneously, with the tensile face of the bottom beam at top, and the tensile face of the top beam down. The loading system was self-adjusting so that constant load was applied at all times during the experiment. Four point loading was applied to the beams over a span of 3000 mm with a constant moment region of 1000 mm in the middle. The process of corrosion was accelerated using an impressed current of 215 mA under controlled humidity and continuous spray of ultrafine mist on the beam specimens kept inside a polyethylene cover.

The beams were constantly monitored (once every two hours) for the appearance of the first corrosion crack. It was found that for beams corroded under sustained load, the crack appeared after 53 hours whereas for beams corroded in the absence of load, first cracks were observed at 95 hours. Also, corrosion crack widths in the corroded region were found to increase monotonically with time, though at a decreased rate.

At the end of corrosion, crack maps were drawn for each beam. For beams without sustained load, two cracks running parallel to the reinforcements on the bottom face were observed. For beams under sustained load, in addition to these two longitudinal cracks, two additional discrete cracks were observed at the sides of the beams. Corrosion crack widths were measured using a demec gauge.

After completion of corrosion, the beams were tested to failure following which six coupons, three from each tensile rebar, each 30-50 mm in length, were extracted from the corrosion zone. They were cleaned and weighed to determine the mass loss. It was found that at lower mass loss (<15%), the mass loss in beams corroded under load was about 8% more than in beams corroded without load. However, at higher mass loss (>20%), the mass loss for both beams was almost equal.

Figure 2.5 shows the load-deflection curves for specimens of groups A and B. The curves for beams of group A show that although there was no significant effect of corrosion on the

cracking load, reductions of approximately 8, 14, 25 and 34% in the yield load and 7,11, 20 and 29% in the ultimate load were observed after 50, 110, 210 and 310 days of corrosion exposure. For the curves of beams of group B, reduction in yield loads were 11 and 18% and reduction in ultimate loads were 12 and 14% after 50 and 110 days of corrosion. At 210 and 310 days of corrosion exposure under load, no correlation was observed between the presence of flexural cracks (due to sustained load) and reduction in beam strength.

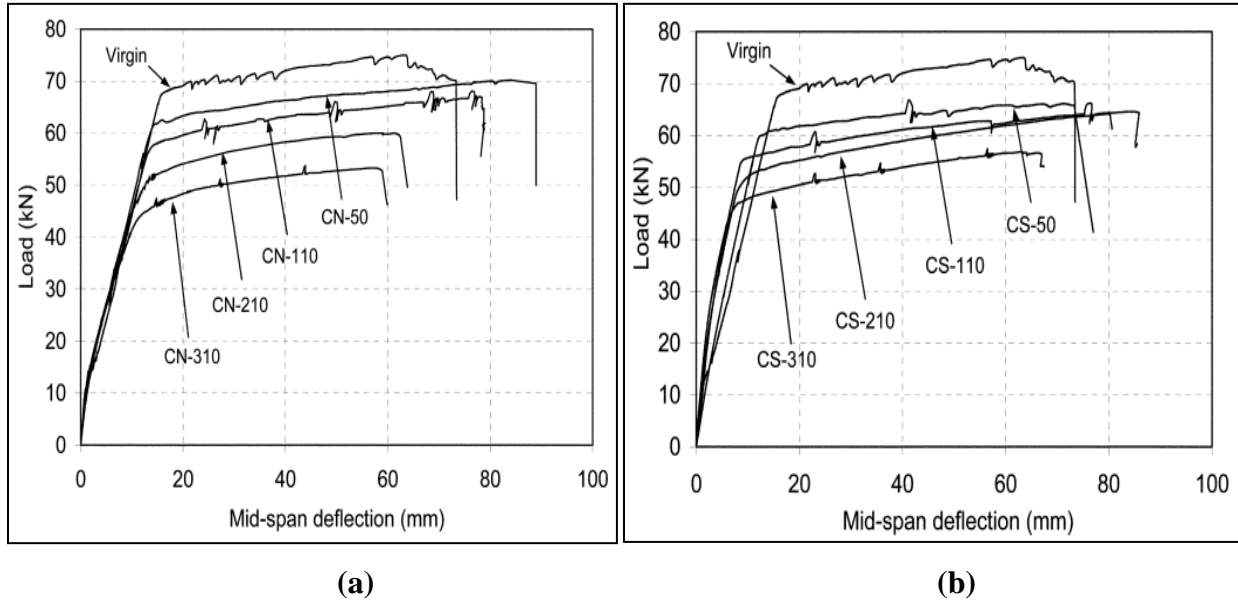


Figure 2.5: (a) Load-deflection curves for specimens of group A; (b) Load-deflection curves for specimens of group B [15]

Due to the sustained load on the beams, flexural cracks appeared, which decreased the time to first visible corrosion crack. The time from corrosion initiation to cracking was reduced by 44% when beams were corroded under the 60% load.

Also, the corrosion crack width increased at a rate of 22% for the beams under sustained load for the first 50 days, after which time it decreased and became almost identical for both types of beams. [15]

Malumbela et al. (2009) conducted an experimental study on the corrosion of RC beams while being subjected to constant sustained service loads. The RC beam specimen had dimensions of 153 mm x 254 mm x 3000 mm with three 12 mm ribbed bars as tension reinforcements, two 8 mm plain bars as compression reinforcement, and stirrups of 8 mm diameter at 100 mm centre-

to-centre spacing in the shear span only. The cover thickness was 40 mm. In the middle span, 8 mm dia. hooks were used at 200 mm spacing instead of stirrups. The concrete mix was designed to give a 28-day compressive strength value of 35 MPa. Maximum aggregate size of 13.2 mm and water/cement ratio of 0.7 was used.

A loading frame was set up to apply four point bending on the beams. The tensile face was kept at top, so as to monitor the growth of cracks and tensile strains easily, to construct a 5% NaCl solution pond (50 mm height x 700 mm length) on the tensile face, and to facilitate repair and strengthening of the corroded beams whilst under sustained loads. The sustained load levels used in this study were much lower than those used by other researchers (0%, 1%, 8% and 12% of the ultimate load capacity of the control beam). The authors reasoned that this was done to test the beams at the cracked and un-cracked flexural stages of the service life of the beams.

The corrosion of the beams was concentrated over the middle 700 mm length region only. The pond was filled with 5% NaCl solution, and a 12 mm stainless steel bar of length 250 mm was placed in the NaCl solution, which acted as the counter-electrode. Corrosion of beams was accelerated by using an impressed current of 150 mA. The direction of current was such that the tensile steel bars served as an anode while the stainless steel bar served as a cathode. Further, 4 days wetting and 2 days drying cycles were used. The current was only applied during the wetting period. Longitudinal strains on the tensile and compressive faces of beams were measured before and after each wetting cycle using a 100 mm demec gauge. Lateral strains on top and side faces were also monitored during the test.

The results were shown in terms of variations with time of longitudinal strains, second moment of area, curvature and depth of neutral axis of the beam tested under simultaneous load and corrosion. The following conclusions were drawn by the authors from the results obtained:

- Longitudinal tensile strains on corroded beams under a sustained load are influenced mostly by the level of corrosion of steel bars.
- Longitudinal tensile strains, curvatures, and effective second moments of area of corroded beams increase monotonically with time at a decreasing rate, provided that no corrosion creep rupture occurs

- Depth of neutral axis of beams corroded under service loads is independent of level of corrosion for beams without flexural cracks, but reduces significantly with an increase in corrosion level in case of beams with flexural cracks.[16]

Hariche et al. (2012) carried out experiments to study the effect of corrosion of reinforcement on serviceability behavior under sustained loads. The main parameters were the reinforcement configuration and the sustained load level. Four series of beams, each containing six specimens of dimensions 100 mm x 160 mm x 1500 mm were tested. Out of the six beams in a series, three were corroded under load while the remaining three were corroded without load. In the first three series, sustained load of 20 kN was applied. For the fourth series, the load value was 30 kN. Three arrangements of tensile reinforcements were used in the experiments. For the first and the fourth series, tensile reinforcement consisted of two high strength deformed bars of diameter 12 mm. For the second series, tensile reinforcement consisted of a single high strength deformed bar of dia. 16 mm, while for the third series; it consisted of three high strength deformed bars of dia. 10 mm. For all series, compressive reinforcement consisted of two mild steel bars of dia. 8 mm. Mild steel stirrups of dia. 8 mm were only provided in the shear span at 60 mm spacing. Also, the stirrups were covered with plastic at contact points with tensile bars so that the corrosion of only tensile bars was done.

Impressed current technique was used to corrode the reinforcement, with an approximate current density of 150 mA/cm^2 . A data logger recorded the values of current in the bars every hour during the test period. For the corroded beams, a 3% NaCl solution was used as electrolyte, whereas for the uncorroded beams, plain water was used. The rate of corrosion of the beams was measured using Faraday's law as well as gravimetric mass loss.

It was found that the current efficiency (ratio of charge consumed in the oxidation of Fe in steel to the total charge passed) was higher for a single large bar of series 2 of beams, rather than for smaller bars in case of series 1, 3 and 4. Even though the tensile reinforcement area values were close to each other, the beams with two Y12 bars and those with Y10 bars performed better in terms of deflection than the beams with only one Y16 bar. Also, longitudinal corrosion cracking occurred mainly on sides for beams of series 1 and 3, whereas for series 2, crack was observed at bottom face. [17]

Du et al. (2013) carried out experiments to study the effect of simultaneous loading and reinforcement corrosion on the structural behavior of RCC beams. Five under-reinforced RCC beams of dimensions 100 mm x150 mm x1300 mm were cast, using two 8 mm diameter ribbed bars (tension reinforcement), two 6 mm diameter plain bars (compression reinforcement) and 6 mm diameter plain bars as stirrups at a spacing of 100 mm. Ordinary Portland Cement (OPC) with a cement content of 270 kg/m³ was used in the concrete mix. Maximum size of aggregates was 10 mm. Water to cement (w/c) ratio was kept at 0.65. Additionally, 3.5% calcium chloride by mass of cement was added to the mix in order to improve the electrical conductivity of the concrete.

The beams were cured in a water tank for 28 days, following which they were further exposed to air in the laboratory for 29 days. After this, they were subjected to a sustained load of 15 kN (60% of the design ultimate load) at mid-span using a loading rig. Deflection was measured using a dial gauge. Out of the five beams, four were corroded for a period of 50-60 days using impressed current and wet-dry cycles to accelerate the corrosion process. The location and length of the corroded reinforcement were the parameters of the study. The intensity of direct current used was 0.25 mA/cm² during the first two weeks, after which time, it was increased to 0.50 mA/cm². To further improve the electrical conductivity of the concrete, the beams were subjected to cycles of drying and wetting, i.e. 2 hr spraying of 3.5% sodium solution and 22 hr drying in natural conditions. At the end of the test, amount of corrosion of the reinforcing bars was determined on the basis of mass loss.

Table 2.1 shows the comparison between simultaneous loading and corrosion performed in this work with separate corrosion and loading [19], in which the same mix was used, but with different dimensions (150 x 200 x 2100 mm) and reinforcement detailing. Similar to beams CB1, CB2 and CB3, only 300 mm middle part was corroded. It can be seen clearly that the ultimate strength reduction and deflection reduction were much greater in the case of simultaneous loading and corrosion of reinforcement.

It was also found that the corroded beams failed earlier than the non-corroded one due to excessive deflections at the serviceability limit state. Three out of five beams with 14%, 16% and 19% corrosion (over mid part of beam) failed suddenly due to fracture of their reinforcing bars.

Table 2.1: Effect of loading and corrosion on beam capacity and deflection [18]

Type of beam tests	Beam no.	Amount of corrosion	Ultimate moment (kN.m)	Max. deflection (mm)	Reduction in strength (%)	Reduction in deflection (%)
Simultaneous loading and reinforcement corrosion	CB5	0%	6.13	69.3	0	0
	CB1	14%	3.61	9.20	41	87
	CB2	19%	3.61	8.93	41	87
	CB3	16%	3.61	9.81	41	86
Separate loading and reinforcement corrosion[19]	T680	0%	31.1	87.4	0	0
	T682	9%	28.9	64.4	7	26
	T280	0%	19.5	100	0	0
	T282	12%	17.5	92.5	10	8

The remaining beams with 0% and 27% corrosion (over right half length of beam), did not fail while being corroded. They were further loaded to failure. At the ultimate limit state, the corroded beams displayed reduced strengths and less ductile behavior. Residual strength values varied with the amount of corrosion, location and length of the corroded reinforcements and the bending moment distribution under applied loads. Also, a comparison between the cases of simultaneous loading and corrosion with separate loading and corrosion showed that the adverse effects in terms of reduced strengths and ductility were more pronounced in the case of simultaneous loading and corrosion of reinforcement. [18]

Wang et al. (2014) investigated the effects of micro and macro cracks due to sustained load on reinforcement corrosion in RC beams. For this purpose, 24 RC beams of dimensions 200 mm x 250 mm x 1200 mm were cast using four different concrete mixes (one containing Portland cement and the other containing 35% ground granulated blast furnace slag, both with 0.45 and 0.65 water/binder ratios). Beam reinforcement consisted of two 12 mm diameter bars as tension reinforcement, two 8 mm diameter bars as compression reinforcement, and stirrups of 6 mm diameter spaced at 70 mm in the shear span and 120 mm in the constant moment span. To check

the effect of micro-cracking produced by sustained loads on chloride-induced corrosion, three levels of sustained loads were chosen, i.e. 0%, 50% and 100% of the load that induced flexural cracks of width 0.1 mm on the tension face of the beams.

The tension faces of all beams tested under sustained loads were subjected to wet-dry cycles, each consisting of 1 day ponding with 10% NaCl solution and 6 days drying. These cycles were repeated for a total period of 60 weeks. All other faces except the tension faces of the beams were sealed with epoxy to allow ingress of chloride ions only through the tension faces. Electric potential of steel reinforcement in beams was measured once every two weeks during the test period using a Digital Half Cell (DHC) apparatus. Also the rate of corrosion of beams was measured using the Linear Polarization Resistance (LPR) technique. At the end of the test, concrete dust samples were extracted from different depths of the beams and were analyzed for chloride content determination.

It was found that the beams which were subjected to higher load levels had shorter times to corrosion initiation, higher corrosion potentials and higher corrosion rates. The chloride contents at different depths were also higher for higher load levels. Use of lower water-cement ratio and GGBS resulted in reduced penetration of chlorides. [20]

2.4 CORROSION WITHOUT APPLIED LOADS

Rodriguez et al. (1997) carried out detailed investigations on the effect of corrosion of reinforcement on characteristics of RC beams. In the experimental program, a total of 31 beams of dimensions 150 mm x 200 mm x 2300 mm were cast. Two types of concrete mixes -Type 1(no added CaCl₂) and Type 2(3% CaCl₂ by weight of cement) were used. Also, the 31 beams were grouped into six different types based on the detailing of the reinforcement. Different detailing of reinforcement used is shown in **Table 2.2**.

In addition, Beam Types 12 and 13 had similar reinforcements except that only 50% of the tensile bars in type 13 were anchored outside the support zone. For each series, 2 beams were cast using concrete mix Type 1 (control beams) and 4 cast using mix Type 2(corroded beams). After casting and wet curing for 28 days, the beams with concrete mix Type 2 were subjected to accelerated corrosion for a period of 100-200 days. The current density used was 100 mA/cm². After the beams were corroded to desired levels, detailed crack maps were obtained for each

beam. The values of attack penetration (bar radius reduction) for tension bars and stirrups were calculated using the gravimetric method after the beams were load tested.

TABLE 2.2: Detailing of reinforcement [21]

Beam Type	Reinforcement (dimensions in mm)		
	Tension	Compression	Stirrups
1	2-12 Φ	2-8 Φ	Φ 6@150
11	2-10 Φ	2-8 Φ	Φ 6@170
12	4-12 Φ	2-8 Φ	Φ 6@170
13	4-12 Φ	2-8 Φ	Φ 6@170
21	4-12 Φ	4-8 Φ	Φ 6@170
31	4-12 Φ	4-8 Φ	Φ 6@85

After corrosion, the beams were tested to failure using four-point loading with equal loads applied symmetrically at distance of 200 mm from the mid-section of beams. The loading of the beams was done in two phases. In the first phase, loading was applied in steps of 0.8 mm each, during which readings and cracking patterns were noted at each step. After the expected limit service load was reached, process was stopped for 10 minutes and readings noted. After this, the beam was kept for 10 minutes without load. The second phase involved applying load to beams at a displacement rate of 0.8 mm/min. until the limit service load and a rate of 1.5 mm/min thereafter until the end of test.

It was found by the authors that corrosion of the beams increased their deflections and crack widths at service loads, reduced strengths at ultimate loads, and led to increase in both spacing and width of flexural cracking due to bond deterioration. Different types of failure modes observed by the authors are shown in **Figure 2.6**.

Regarding the modes of failure, Type 1 failure occurred in both corroded and uncorroded beams with low tensile reinforcement ratio, Type 2 failure in beams with uncorroded tensile reinforcement of high ratio and in most of the corroded beams with high shear reinforcement ratio, type 3 failure in almost all beams having a high ratio of corroded tensile bars and large stirrup spacing, and finally, type 4 failure was observed in both corroded and un-corroded beams

with curtailed tensile bars. Thus it was found that corrosion not only causes reduction in bond and flexural strengths, but also causes change in the mode of failure of the beams. [21]

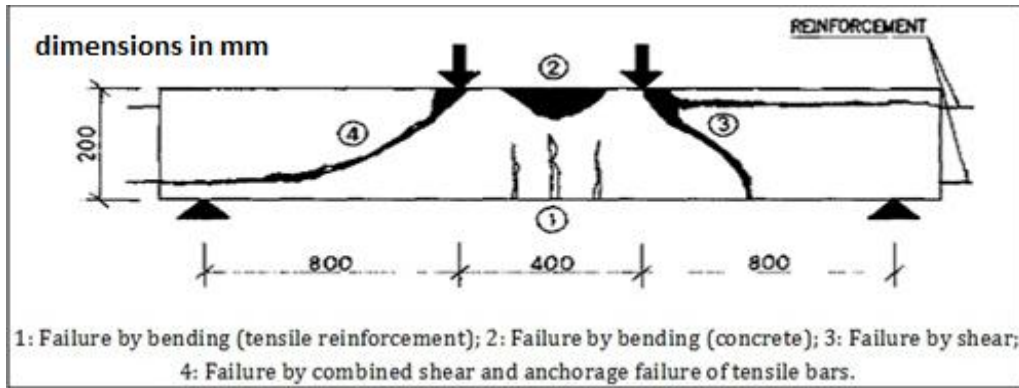


FIGURE 2.6: Observed modes of failure in tested beams [21]

Mangat and Elgarf (1999) investigated the effects of corrosion of reinforcement on the load carrying capacity of 111 under-reinforced concrete beams. The beams had dimensions of 100 mm x 150 mm x 910 mm, and were reinforced with no. 10 bars (nominal diameter 9.52 mm). Stirrups were also provided to avoid shear failure. Corrosion was induced at four different levels by impressing current densities of 1, 2, 3 and 4 mA/cm². The beams were tested under four-point loading after completion of corrosion process.

It was found that the ultimate strengths of the beams decreased as the rate of induced corrosion current was increased. A maximum of 77% reduction in ultimate load capacity was found with a corresponding mass loss of 10%. The load-deflection relationships for the beams were dependent on the rate of corrosion when the degree of corrosion was greater than 2.5%. Also, rate of corrosion was found to have an effect on the flexural load capacity of the beams. When the rate of corrosion was less than 3.75%, it had little effect on the strength, but when it was greater than 5%, increase in the rate of corrosion significantly reduced the strength of beams. On the basis of results obtained from this experiment, they proposed a numerical relation between the residual flexural strength and the rate of corrosion. [22]

Torres-Acosta et al. (2007) performed experimental studies to establish a relation between the loss in flexural capacity and reduction of the steel cross-section due to corrosion of reinforcement. 12 beams of dimensions 100 mm x 150 mm x 1500 mm reinforced with a single

bar of diameter 10 mm in the tensile zone were cast. During the casting process, NaCl (table salt) was added to the mix to obtain a chloride ion concentration of 3% by weight of cement. The chlorides were added over the entire length of the beam. Water/cement ratio used was 0.5.

Acceleration of corrosion was achieved by applying a constant current density of $80 \mu\text{A}/\text{cm}^2$ on the reinforcement (anode). A 30 mm wide and 1200 mm long steel plate which was glued to the beam surface was used as the cathode. The constant current density was applied for a period of approximately 40, 80, or 200 days according to the desired level of corrosion damage. The desired level of corrosion of 5, 10 and 15% radius loss of the bar was estimated using Faraday's law. At the end of the accelerated corrosion process, the beams were inspected for the presence of surface cracks by using a magnifying lens. Also crack widths were measured along each crack. Then the beams were tested to failure by three-point loading, with a central load applied at displacement rate of 1 mm/min.

After testing, the bars were extracted from the beams and average corrosion penetration was estimated from the mass loss. Efficiency of the accelerated corrosion was estimated by comparing the actual mass loss with the one obtained by Faraday's law. Further, each bar was inspected for evidence of pitting and pit depths measured using a vernier caliper. Empirical relationships between the average corrosion penetration (X_{AVER}) and maximum pit depth (PIT_{MAX}) and between the residual load capacity (RLC_{COR}) and maximum load for corroded beams ($P_{\text{MAX-COR}}$) were obtained.

From the results obtained, the authors concluded that corrosion in dry environment was more favorable to crack evolution than corrosion done in wet environment. Also, the corrosion efficiency was found to be greater for wet environment (92.3%) during accelerated corrosion than for dry environment (73%). Loss in load capacity was 30% to 40% for average radius loss of reinforcement (measured as ratio of average corrosion penetration to the original diameter of bar) of 0.06 and 0.1. Whereas, for the observed case of localized (pitting) corrosion, the load capacity decreased by 60% for an average radius loss of 0.1. [23]

2.5 ACCELERATED CORROSION

Normally, it may take many years for a structure to corrode sufficiently to be of serious concern. Due to a limited amount of time available for experiments related to corrosion, most researchers

have used techniques to effectively accelerate the usually slow rate of corrosion process, or to simulate specific environments such as coastal environments. Thus, results can be obtained in a small period of time.

The various methods used by researchers to accelerate corrosion are explained below:

- **Impressed current technique:** This is the most commonly used method to accelerate corrosion. In this technique, direct current of constant intensity is used in such a manner that the reinforcing steel bars are connected to a positive terminal acting as anodes, while a steel bar/plate is connected with a negative terminal (cathode). An electrolyte (NaCl solution or CaCl_2) is used to provide electrical contact between the anode and the cathode. This increases the flow of electrons in the circuit. The current density in steel due to natural corrosion is generally between 0.1 and 10 $\mu\text{A}/\text{cm}^2$. The level of current density used by the researchers in the past has varied greatly - from 3 $\mu\text{A}/\text{cm}^2$ to 10400 $\mu\text{A}/\text{cm}^2$ [24].
- **Impressed voltage technique:** Some researchers have used this technique to accelerate corrosion rather than using the impressed current technique. This method is same as the impressed current technique except that a constant voltage is applied in the corrosion circuit in place of a constant current.
- **Accelerated depassivation of steel:** For depassivating steel within a short time to initiate corrosion quickly, various methods have been used. Some researchers put chlorides in the concrete mix (1% to 5% by weight of cement). Others immersed their specimens in tanks containing NaCl solution having concentration mostly between 3% and 5%. It is noteworthy that sea-water has a nominal chloride concentration of 3.5% and many researchers have used this level for chloride treatment of the specimens. Further, some researchers have employed spraying or ponding on selected faces of the specimens [24].
- **Wetting-Drying cycles:** Almost all of the researchers have used wetting-drying cycles to accelerate corrosion. In the coastal areas, the most critical parts of a structure are those which are exposed to tidal waves or splashing by sea-water. In contrast, permanent submersion of the structural element is less severe in terms corrosion. Cyclic wetting and drying causes continuous movement of moisture through the concrete pores and leads to greater accumulation of harmful species in the concrete [25].

- **Alternative methods:** Some researchers have used other methods, such as using artificial climate environments similar to natural ones, acceleration of chloride ion diffusion to reduce time to depassivation of steel, and the accelerated chloride migration test (ACMT). However, their use in experiments has been limited.

In the present case, corrosion process was accelerated by means of the impressed voltage technique (constant applied voltage of 20V) and 3.5% NaCl solution sprayed on to the specimens. Though the acceleration of corrosion by these artificial means does not reflect the actual conditions under which corrosion occurs, it provides results in a reasonable time period, and hopefully gives accurate estimates to the corresponding values of parameters measured in natural environments.

2.6 AIM OF PRESENT RESEARCH

From the above review of research work done on the effect of corrosion of reinforcement in beams under different conditions on load-carrying capacity, it is clear that corrosion in RC beams subjected to a loading history (in terms of sustained loads and pre-loads) has a significant effect on the corrosion process occurring in RC beams. It is also observed that the application of pre-loads or sustained loads affects the structural behavior of RC beams differently. Though the structural effects of sustained loads whilst corrosion are more severe than the application of pre-loads on the beams (in terms of reduced load-carrying capacity and ductility, service life reduction), investigations on RC members subjected to pre-loads are important due to high probability of such situations occurring in practice, e.g. the case of bridge members where high sustained loads are not likely to be applied during corrosion, or in the case of buildings which may be overloaded only for short durations due to various reasons (marriages, other events involving large gatherings, proximity to famous sports grounds, etc). Therefore, in the present study, effects of pre-loads on the corrosion process of RC specimens and subsequent effects on ultimate strength, mass loss and failure modes are presented.

CHAPTER 3

EXPERIMENTAL INVESTIGATIONS

3.1 GENERAL

This chapter explains in detail the experimental work done during the study. Details of RC beam specimens, materials, concrete mix design, accelerated corrosion setup used, methodology of the experiment and subsequent testing of beams is elaborated.

3.2 EXPERIMENTAL DETAILS

The experimental work done involves details of beams, concrete mix design, setup for the accelerated corrosion test, pre-loading of beams, finally testing of the beams.

3.2.1 SPECIMEN DETAILS

A total of five beams of dimensions 150 mm x 150 mm x 700 mm have been used in the test program. The beams have been reinforced with two 12 mm bars in the tensile zone, two 6 mm bars in the compression zone, and stirrups of diameter 6 mm with a spacing of 85 mm (**Figure 3.1**). The clear concrete cover to stirrups has been kept at 25 mm. Tensile bars in each beam have been extended to about 35 mm length outside of the beam end-sections to facilitate voltage application.

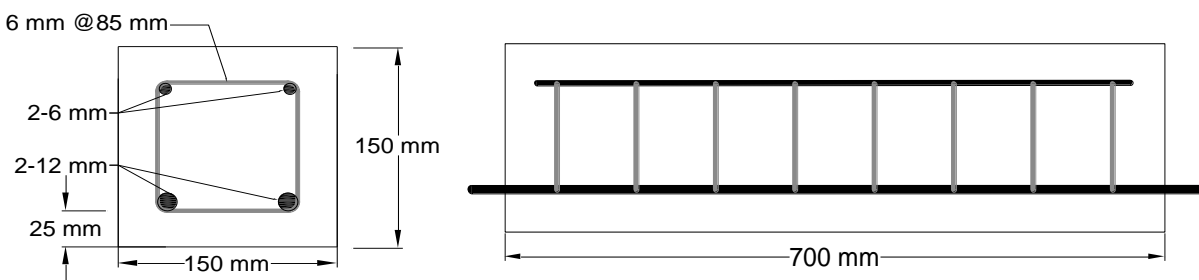


Figure 3.1: Dimensions of the beam specimens

From the analysis according to the procedure outlined in IS 456:2000 [21], an ultimate bending moment capacity of 8.35 kN.m has been determined for the RC beam specimen used. Also, the beam has been strengthened to avoid shear failure by providing stirrups at a spacing of 85 mm c/c.

3.2.2 MATERIALS

The materials used in the casting process of the beam specimens are fine aggregates, coarse aggregates, cement, water and reinforcing steel. These are discussed below:

- **Fine aggregates** have been obtained locally. River sand which conformed to Zone IV as defined by IS 383:1970 [22] has been used in the mix design. Bulk Specific gravity of the sand has been found to be 2.608 and water absorption has been found to be 3.6%. The fineness modulus of sand has been obtained by sieve analysis as shown in **Table 3.1** and its value determined to be 1.57.

Table 3.1: Sieve analysis of the fine aggregates.

Sieve size	Mass retained (g)	Percent retained	Cumulative percent retained
4.75 mm	19	1.93%	1.93%
2.36 mm	19	1.93%	3.86%
1.18 mm	26	2.64%	6.5%
600 μ	25	2.53%	9.03%
300 μ	313	31.74%	40.77%
150 μ	534	54.16%	94.93%
Pan	50	5.07%	Total percentage = 157.02%
	Total : 986 g		FM = 157.02/100 =1.57

- **Coarse aggregates** have been also obtained locally. Crushed rock aggregates of angular shape and nominal maximum size 10 mm have been used in the mix design. The bulk specific gravity and water absorption of the coarse aggregates have been found to be 2.609 and 0.7% respectively. The fineness modulus of coarse aggregate has been found to be 6.29 as shown in **Table 3.2**.
- **Cement** has also been obtained fresh from a local supplier and kept in dry condition. The cement used has been Ordinary Portland Cement (OPC) grade-43 as per IS 8112:1989 [23]. Some important properties of the cement have been found by performing experiments and are shown in **Table 3.3**.

- **Water** which has been used in the mix is ordinary tap water obtained from the laboratory itself.
- **Reinforcing steel** has also been obtained from a local supplier. All the 12 mm and 6 mm bars used for reinforcement have been ribbed TMT bars of grade Fe 500D manufactured by Jyoti Pvt. Ltd.

Table 3.2: Sieve analysis of the coarse aggregates.

Sieve size	Mass retained (g)	Percent mass retained	Cumulative percent retained
80 mm	0	0%	0%
40 mm	0	0%	0%
20 mm	0	0%	0%
10 mm	971	32.39%	32.39%
4.75 mm	1945	64.88%	97.27%
Pan	82	2.73%	Total = 129.66%
	Total: 2998 g		FM = (129.66+500)/100 =6.29

Table 3.3: Properties of the Cement used.

Cement property	Calculated Value
Grade	OPC 43
Company	JK Lakshmi
Standard Consistency	28%
Initial Setting time	152 minutes
Final Setting time	261 minutes
28 day compressive strength (average of 3 cubes)	47.3N/mm ²

3.2.3 CONCRETE MIX DESIGN PROCEDURE

Concrete mix design is a process of selecting optimum quantities of ingredients to meet the desired properties of concrete in both its fresh and hardened state. It is a well established practice around the world, and there are many methods for calculating mix proportions of a concrete mix. These methods are mostly based on empirical relations, charts, tables and graphs developed on the basis of extensive experiments performed on locally available materials. The Indian codes allow mix design by various methods. In this study, the mix has been designed according to the method outlined in IS 10262:2009 [24] which is based upon the absolute volume concept.

A concrete mix using the above mentioned materials has been designed to achieve a grade of concrete of M25. The water/cement ratio used for all beams has been 0.45 for a slump value between 70-100 mm. The mix proportions of the constituent materials has been determined and is presented in **Table 3.4**. A total of three trial mixes have been prepared. The water content has been adjusted in the mixes due to bleeding which has been observed in mixes 1 and 2. In mix 3, no bleeding has been observed. A total of 9 cubes of dimensions 150 mm x 150 mm x 150 mm, 3 of each mix, have been cast. Mix 3 has been selected as the mix to be used in design. Average compressive strength of three cubes of Mix 3 at 28 days has been found to be 33.2 MPa, which is an acceptable value for M25 grade concrete.

Table 3.4: Concrete mix proportions

No.	Material	Weight/m ³	Notes
1	Water	197.6 kg	Tap water used
2	Cement	439.1 kg	OPC 43 used
3	Fine aggregate	561.2 kg	Zone IV sand
4	Coarse aggregate	1089.8 kg	10 mm max. nominal size
Mix proportions (C:FA:CA) = 1:1.28:2.48			

3.2.4 BEAM CASTING AND CURING

The beams have been cast using steel formworks in three stages. The two end parts perpendicular to the longitudinal axis of the formwork have been removed and replaced with wooden faces to

allow for the extension of the tensile bars outside the beam. The aggregates have been washed and dried in the sun for a day prior to casting. The water content has been adjusted accordingly.

The concrete has been mixed using a electric mixer for about two minutes, after which it has been quickly poured into the formwork. For compaction of concrete, the beams have been kept on a vibrating table while pouring concrete for not more than 2 minutes. Care has been taken to avoid over-compacting the the concrete, which could have led to bleeding.

After casting, the beams have been levelled at the top surface and kept undisturbed for a period of approximately 24 hours, after which they have been removed from the moulds and labeled as B1, B2,B3,B4 and B5. Curing has been done by wrapping the beams with wet gunny sacks, which have been sprayed with water twice a day for the first seven days, and once a day afterwards till the 28th day. After the 28th day, the beams have been air cured in natural environment for about 10 days before they have been installed in the accelerated corrosion setup.

3.2.5 ACCELERATED CORROSION SETUP

Accelerated corrosion is the method of speeding up the process of corrosion in structural elements by means of externally applied electric current and cyclic wetting and drying with a salt solution. Most of the researchers in the past have used these methods to accelerate corrosion process and obtain results in a limited time period. A schematic of the accrelerated corrosion setup used in this study is shown in figure 4. Constant voltage of 20V has been applied using a pre-regulated dual DC power supply equipment of make “Scientech”. The positive terminal of the DC power supply has been connected with the tensile rebar with the help of a metallic clip, while the negative terminal has been connected with a steel wire mesh, which has been wrapped around the beam in its middle third portion. A rectangular piece of gunny sack wrapped between the beam surface and the wire mesh to help maintain conductivity of current between the anodic and cathodic regions of the corrosion cell. The 3.5% NaCl solution, made by dissolving 35 g common salt in a litre of water , has been applied on the middle region (**Figure 3.2**) with the help of a plastic pipe connected with a small tank of capacity 40 litres.

The salt water solution has been sprayed on to the beams two times a day (one at around 10:00 am and other at around 6:00 pm). The tap has been checked in between these intervals for providing adequate flow of water through the pipe.

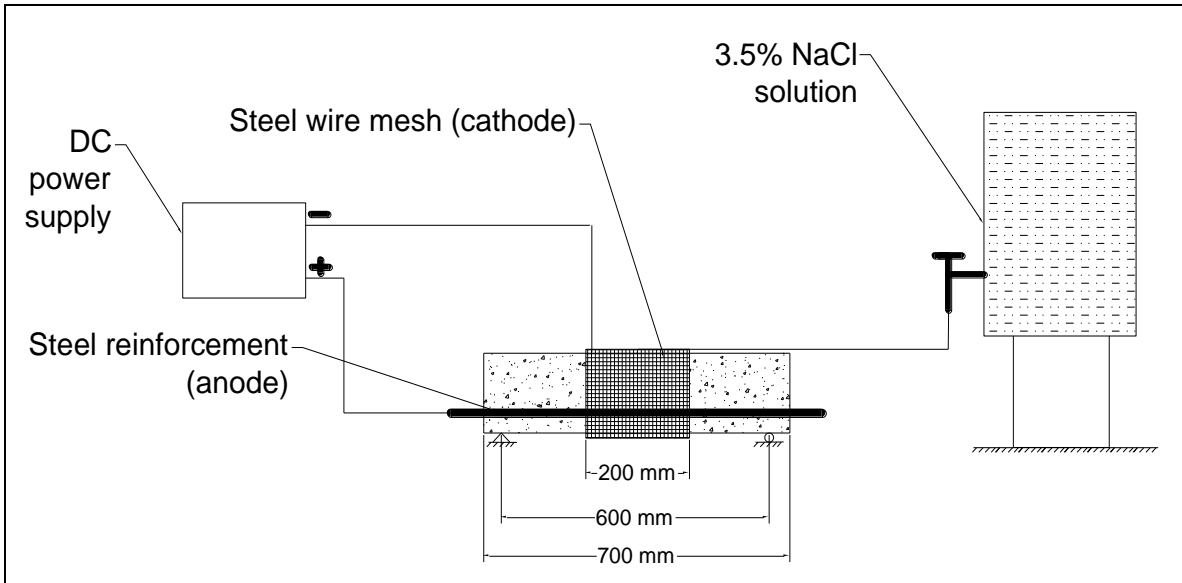


Figure 3.2: Schematic of the accelerated corrosion setup.

The beams have been corroded by two methods as described below:

- The beams B2 and B3 have been connected in a parallel circuit using single port of the DC power supply as shown in **Figure 3.3**.
- The beams B4 and B5 have been also connected in a parallel circuit using a single port of the DC power supply similar to the connection shown in **Figure 3.3**.

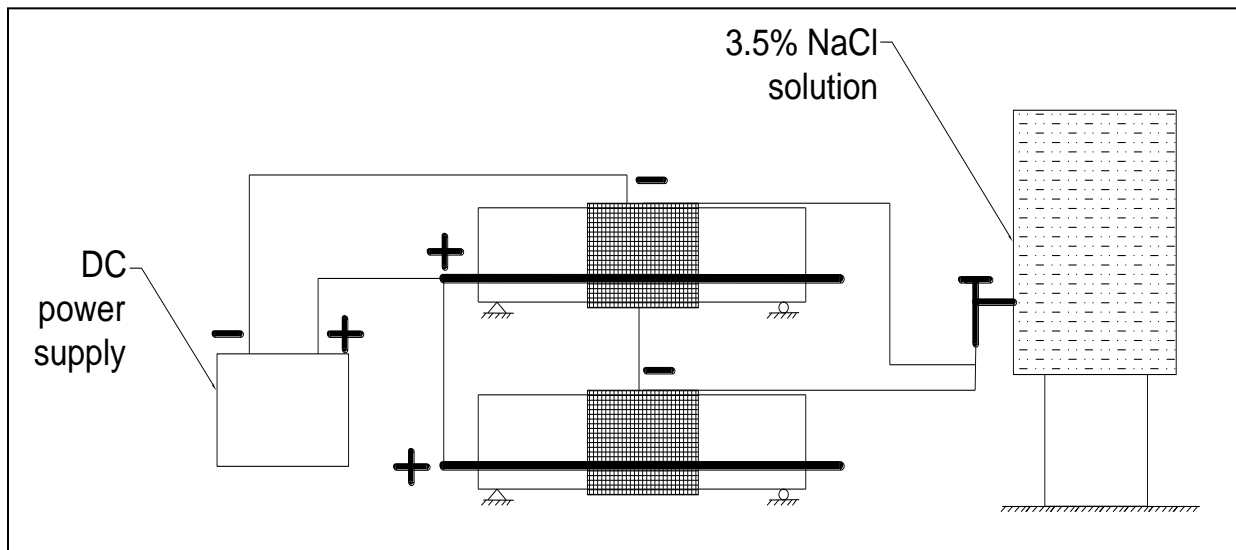


Figure 3.3: Schematic for parallel connection of the beam specimens.

Since a multimeter has been not available during the test of these beams, individual current for each beam could not be measured. The voltage value of 20V has been constant for each beam due to the parallel connection.

- The beam B1 has not been corroded.

3.2.6 PRE-LOADS AND SUSTAINED LOADS

The main parameters investigated in this study have been the effects of varying levels of pre-loads on the RC beams under corrosion exposure. The control beam B1 has been tested under four-point loading immediately after completion of 28 days curing process. A computer-controlled Universal Testing Machine (Hung Ta Instruments Ltd.) with capacity of 1000 kN has been used for this purpose. The rate of loading has been kept equal to 10 kN/min. Visible flexural cracks appeared on side faces at an approximate load of 70 kN. The beam failed at 143.1 kN load value. The pre-loads and sustained load of 1% ultimate load of B1 have been applied on the remaining beams as follows:

- The beams B2, B3, B4 and B5 have been loaded in the UTM in four-point loading up to the pre-defined loading levels, i.e. up to 35.7 kN, 71.4 kN, 107.1 kN and 71.4 kN respectively. The rate of loading has been kept the same as for B1 at 10 kN/min. After reaching the respective load values the tests have been terminated and the beams kept aside for corrosion.
- The beam B5 has further been loaded with a sustained load of 1% of the ultimate load capacity of the beam B1 during the corrosion period. The arrangement used for imposing of the load on the beam in four-point loading is shown in **Figure 3.4**. The weights kept on the beam have been measured to give an approximate load of 143.1 kg (1% load value of B1) being applied to the beam approximately at the ends of the middle portion of the beam.

Each beam has been corroded for a nominal duration of 15 days. After 15 days they have been removed from the corrosion setup, their surfaces cleaned of the corrosion products (rust) and kept aside for testing.

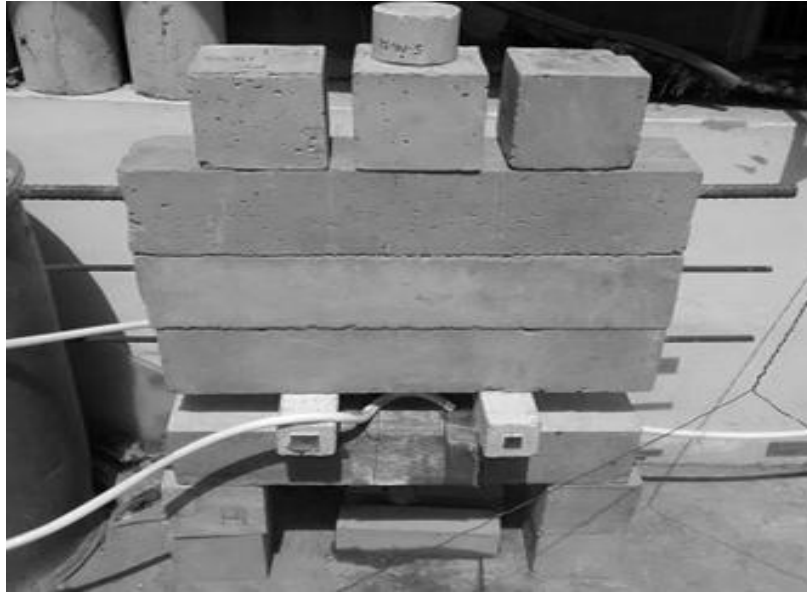


Figure 3.4: Sustained load of 1% on beam B5.

The loading scheme for all beams tested is summarized in **Table 3.5** below.

Table 3.5: Loading program for the beams during corrosion.

Beam no.	Corroded/not corroded	Sustained load	Pre-load
B1	Not corroded	0%	0%
B2	Corroded	0%	25%
B3	Corroded	0%	50%
B4	Corroded	0%	75%
B5	Corroded	1%	50%

3.2.7 TESTING OF BEAMS

After corrosion, the beams have been load-tested in the UTM. Locations on beams have been marked for the applications of load. Load has been applied onto the beam in the four-point loading arrangement as shown in **Figure 3.5**. The observations have been recorded using inbuilt software on the computer which has been connected with the UTM and which plotted real-time load vs. deflection graphs for the beams tested. Load-deflection data values have been obtained from the software.

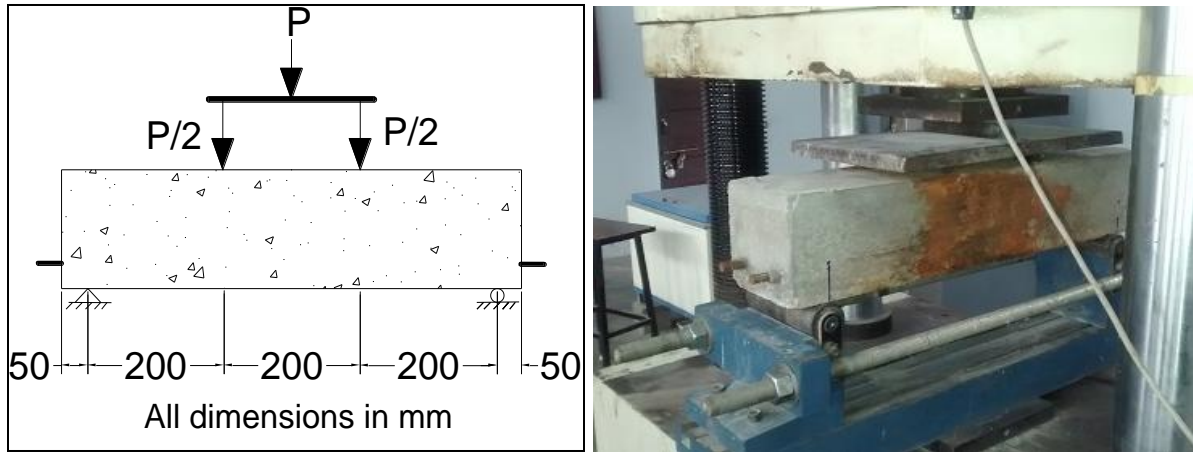


Figure 3.5: Four-point load testing arrangement of the beams.

Another variable to be measured is the amount of corrosion. The amount of corrosion has been measured by the *Gravimetric mass loss technique*, which involved extraction of tensile bars after testing them to failure. The bars have been immersed in a 3.5% Hydrochloric acid solution to wash away the corrosion products (rust) accumulated around the rebars. Tensile bars of the virgin beam B1 have been weighed before immersing in the HCl solution. After 90 minutes, all bars have been taken out, cleaned with a wire brush and water and labeled for identification. All the bars have been then weighed using an electronic balance of least count 1 gram. After weighing, the amount of corrosion has been found by the following equation [18]:

$$Q_{corr} = \frac{(W_0 - W_c - \Delta W)}{W_0} \times 100\%, \quad \dots\dots 3.2$$

where, Q_{corr} is the amount of corrosion of the reinforcement (%), W_0 is the weight of the non-corroded bar per unit length (g/mm), W_c is the weight of the corroded bar per unit length (g/mm), and ΔW is the weight loss of non-corroded bars due to removal of the base metal (steel) by the acid solution (g/mm).

After the determination of the mass loss values, 457 mm (18 inch) specimens have been cut out from the middle portion of the tensile bars. These reinforcement specimens have then been tested in tension in the UTM machine to determine their ultimate strength values.

3.3 CLOSING REMARKS

Every experimental study involves dealing with some uncertainties caused due to effects which are not under control. In the present study, the beams have been corroded while being subjected to outdoor exposure. Therefore, small variations in results due to temperature and humidity changes during the period of the experiment (May-July 2015) are expected to occur in this study. Other important point is the application of the sustained load on the beam B5. Due to the absence of a loading frame, the 1% sustained load has been applied using concrete beam and cube specimens as shown in **Figure 3.4**, to simulate four-point loading appropriately.

The results and discussions of the experiments performed have been presented in the next chapter.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 GENERAL

This chapter presents the results obtained from the experimental work done during the study. It also includes analysis and discussions of the results. The results include load-deflection characteristics, modes of failure, amount of corrosion of the beams and tensile strengths of the corroded bars.

4.2 LOAD - DEFLECTION BEHAVIOR

The load-deflection data obtained from the software application UTM 2.0 (developed by Hung Ta Instruments Ltd.) has been plotted to obtain load-deflection curves for the 5 beams. As mentioned earlier, in all the cases of loading, the rate has been 10 kN/min. The mid-span beam load has been monitored using a load cell and mid-span beam deflections measured using Linear Variable Displacement Transducers (LVDTs) which have been integrally built into the UTM. The load-deflection curves are presented in figures 4.1-4.5 and are explained below:

- **Figure 4.1** shows the load-deflection curve for the healthy beam B1. This beam has neither been corroded nor pre-loaded. The beam failed at 143.1 kN with a mid-span deflection of 7.75 mm.
- Beam B2 has been subjected to a pre-load of 25% of the ultimate load capacity of B1 before corrosion. The load-deflection curve is shown in **Figure 4.2**. The beam failed at 141.5 kN with a mid-span deflection of 7.6 mm.
- The load-deflection curve of the beam B3, which has been subjected to a pre-load of 50% of the ultimate load capacity of B1, is shown in **Figure 4.3**. The beam failed at a load of 137.2 kN with a corresponding mid-span deflection of 8.95 mm.
- The beam B4 has been pre-loaded to 75% of the ultimate load capacity of the beam B1 before corroding it. The beam failed at a load of 127.4 kN with a mid-span deflection of 7.74 kN. The load-deflection curve is shown in **Figure 4.4**.
- Finally, beam B5, which has been pre-loaded to 50% of the ultimate load capacity of B1 and then subjected to a 1% sustained load value while corrosion has been tested. The beam failed

at an ultimate load of 135.45 kN and a mid-span deflection of 7.9 mm. The load-deflection graph is shown in **Figure 4.5**.

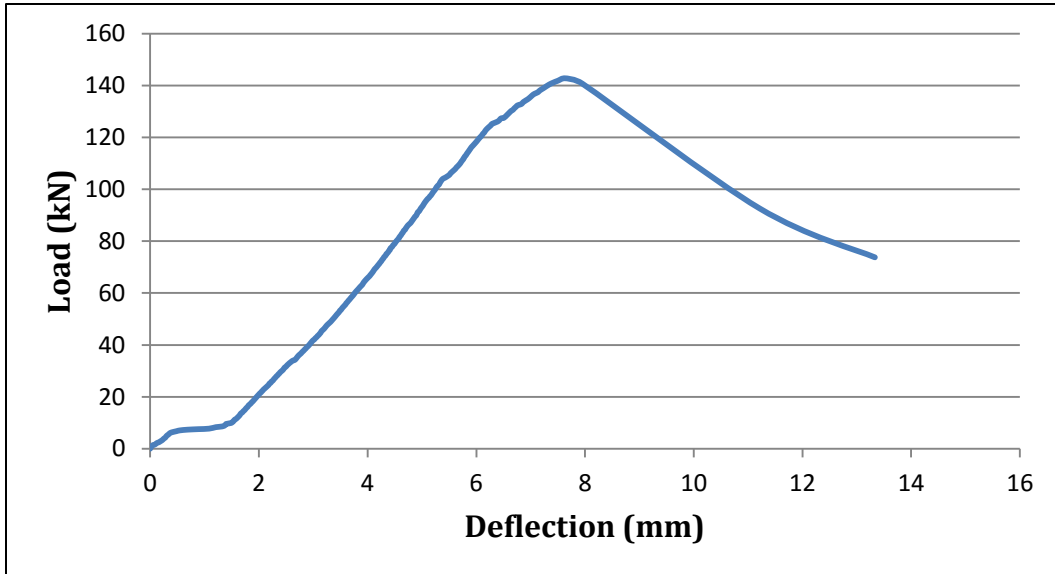


Figure 4.1: Load-deflection curve at mid-span section of beam B1.

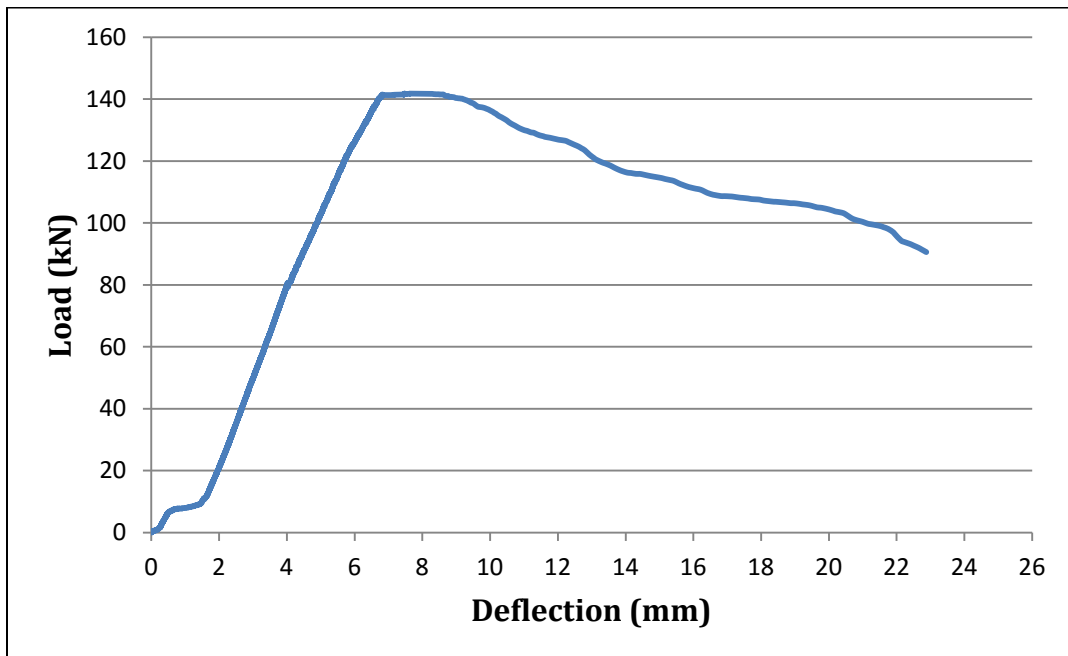


Figure 4.2: Load-deflection curve at mid-span section of beam B2.

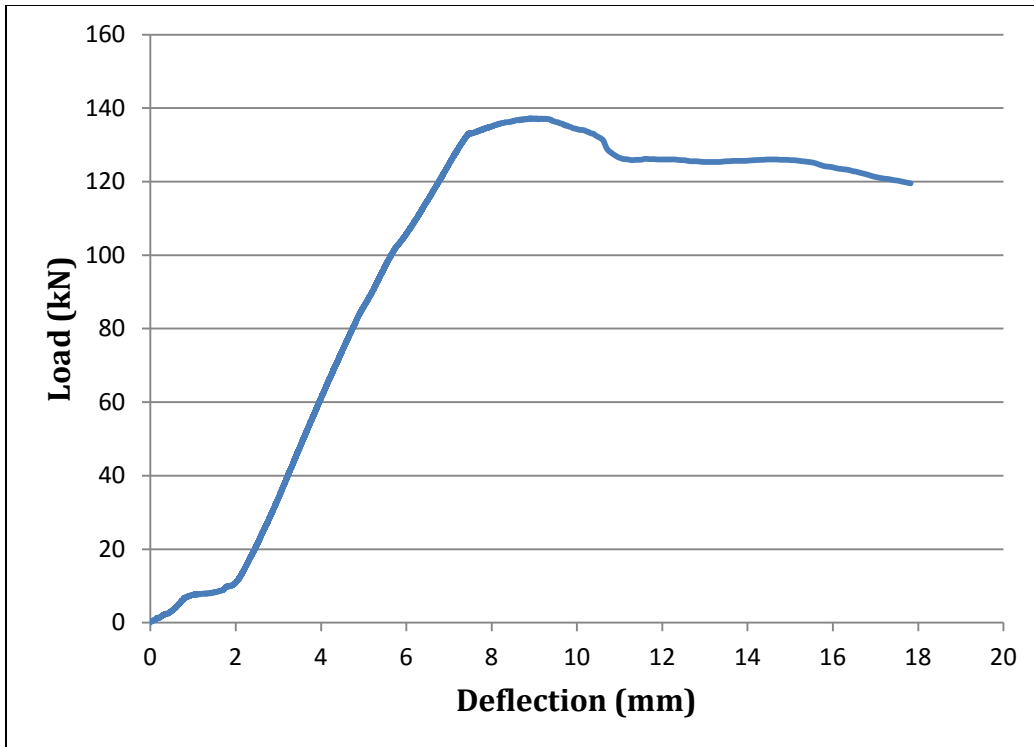


Figure 4.3: Load-deflection curve at mid-span section of beam B3.

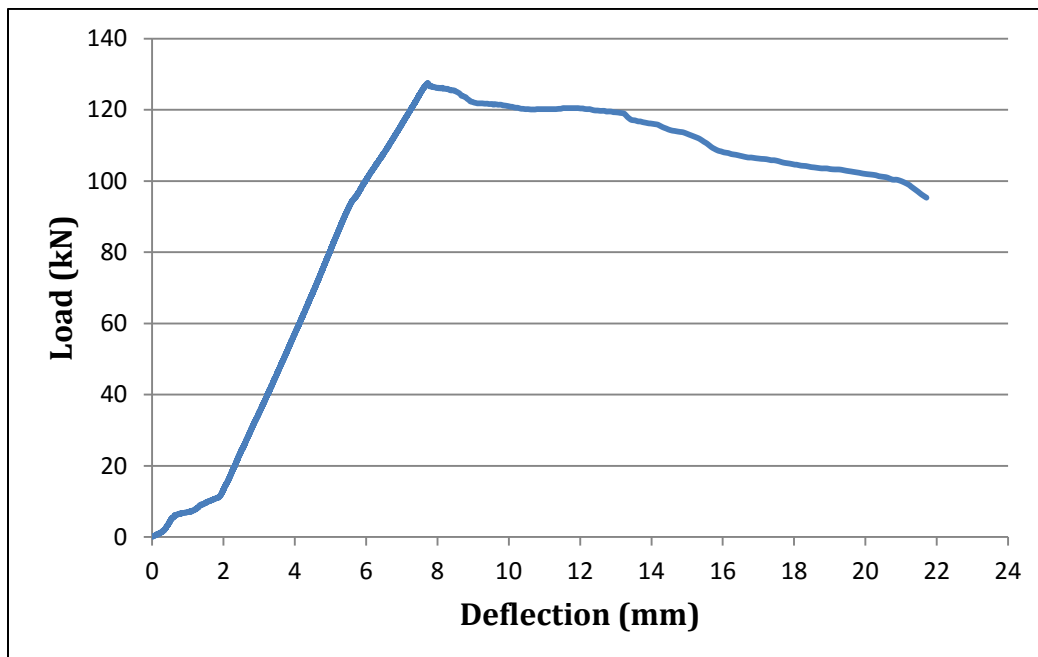


Figure 4.4: Load-deflection curve at mid-span section of beam B4.

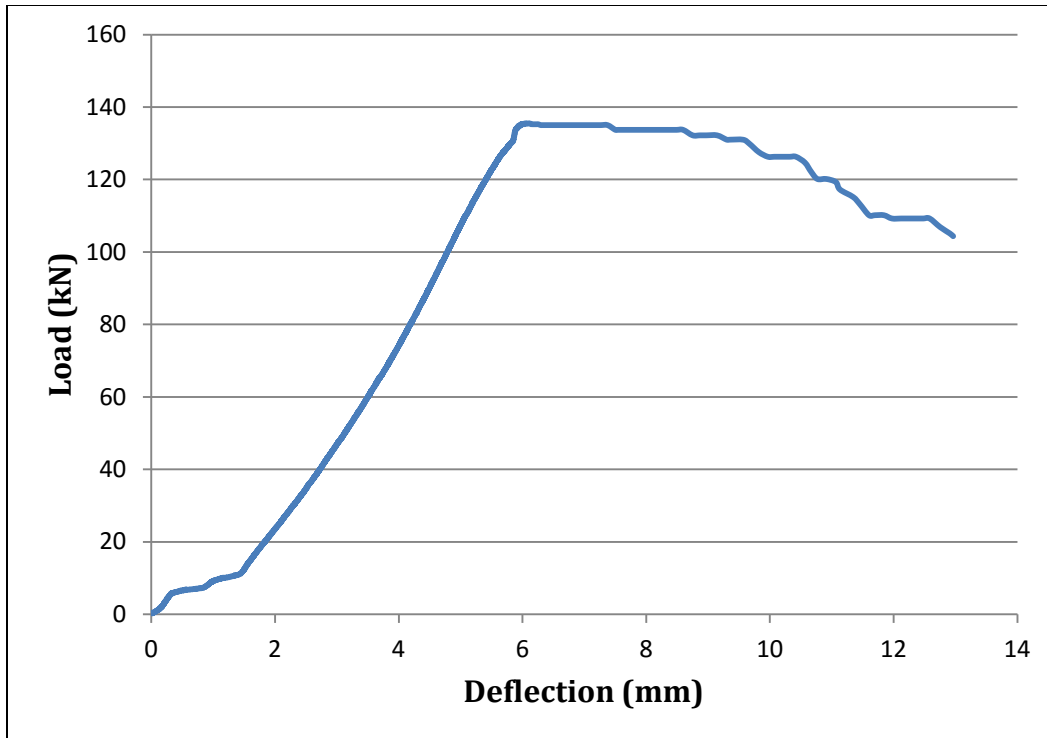


Figure 4.5: Load-deflection curve at mid-span section of beam B5.

4.2.1 DISCUSSIONS

In terms of **ultimate load capacity**, it is found that the healthy beam B1 failed at a load of 143.1 kN. The other four beams have lower ultimate load-carrying capacities. The ultimate load-carrying capacities of these beams are observed to be decreasing with increasing level of pre-loads applied before corrosion. The loss of strength for the 25%, 50% and 75% pre-loaded beams is 1.12%, 4.1% and 10.97% respectively. The loss of strength is found to be very less in the case of the 25% pre-loaded beam B2. This can be explained by the very small crack-widths corresponding to this load-level, which cause strict limitations on the ingress of the chlorides and subsequent deterioration of the beam. Also, the phenomenon of self-healing of concrete at small crack-widths, which leads to closure of the cracks can account for the low value of reduction of the ultimate load capacity of this beam.

Also observed has been that the ultimate load capacity of beam B5 (50% pre-load, 1% sustained load) is slightly lower than that for the beam B3 (50% pre-load, no sustained load). This behavior

can be attributed to the phenomenon of the partial closure of cracks upon the removal of load which is expected to occur more prominently in the beam B3 than in the beam B5. The 1% sustained load applied during corrosion of B5 prevents the full reduction of its crack-widths upon the removal of the pre-load, thereby leading to greater ingress of chloride ions and subsequently more corrosion and loss in its ultimate load capacity.

4.3 MODES OF FAILURE

Corrosion of reinforcement in beams can alter the mode of failure of the beam specimens. This observation has been reported by many researchers in the past. In the present study the modes of failure of all five beams have been observed. The observed types of failure have been compared with those observed by [21] (**Figure 2.6** of Chapter 2).

It has been observed that the beam B1 failed primarily with respect to shear with a major diagonal crack originating from the support section. Thus, the beam B1 failed in shear mode.

Beams B2, B3, B4 and B5 failed in flexure. **Figure 4.6** presents the observed failure mode for B5.



Figure 4.6: Observed failure mode of beam B5.

4.3.1 DISCUSSIONS

The load-deflection curves for the beams B1 to B5 have been superimposed upon each-other to compare their **load-deflection behavior** and **failure modes** in **Figure 4.7**.

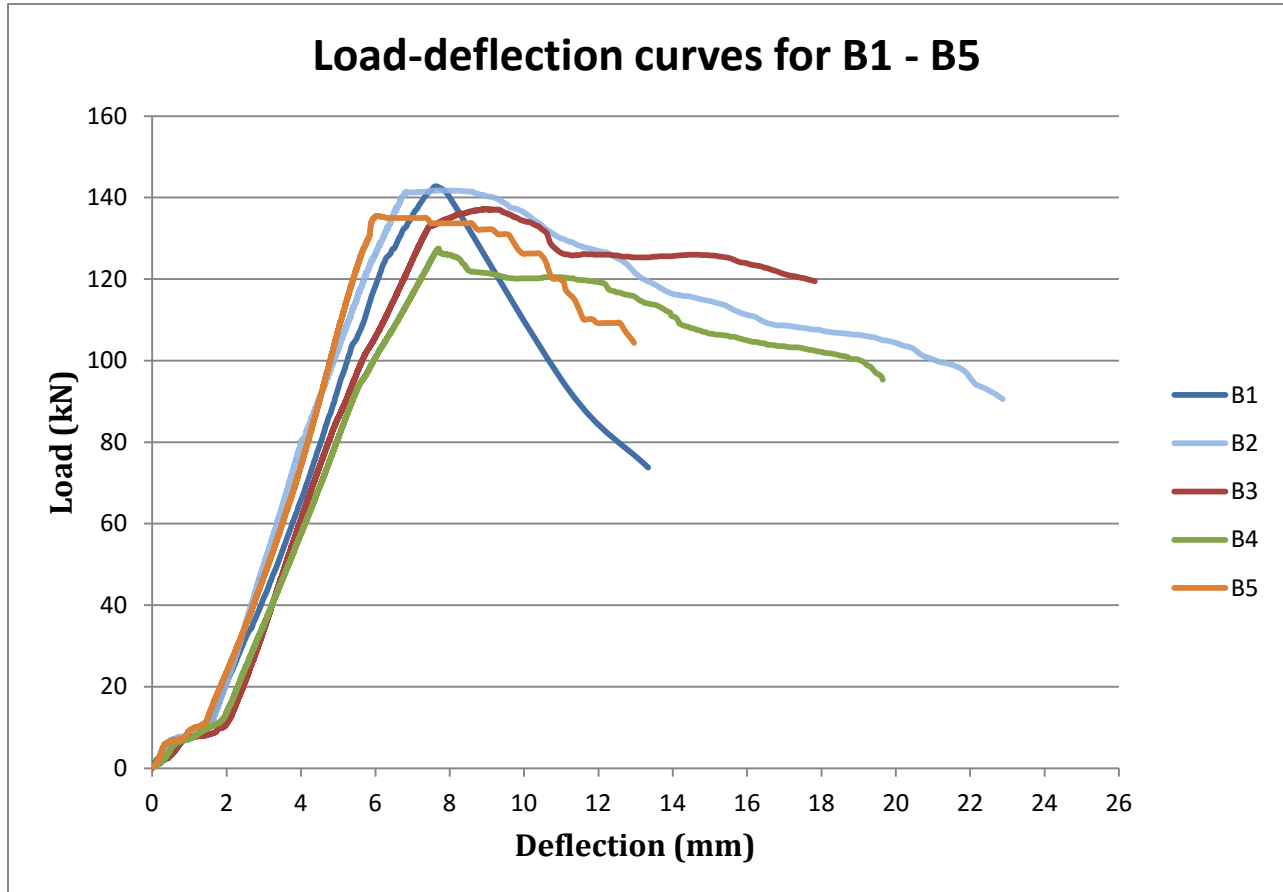


Figure 4.7: Mid-span load-deflection curves for beams B1 to B5.

- It can be seen clearly from the graph that the healthy beam B1, which is neither pre-loaded nor corroded, does not display ductile behavior as is evident from the plateau-regions observed after peak load in curves for beams B2, B3, B4 and B5. The reason for this could be the reduction of the tensile steel area in the corroded middle portion of the beam, which changed the mode of failure from shear to flexure type in the corroded beams.
- In the literature reviewed during this study, it has been observed that in their experiments, many researchers found that the mode of the failure of the beams changed from ductile (higher ultimate loads and deflections with large number of flexural cracks) to brittle (lower ultimate loads and deflections, with very limited flexural cracks). The beams used in these

experiments have been designed to be under-reinforced. However, the beams used in this study have been found to be slightly over reinforced (which explains the brittle shear failure observed in beam B1) and consequently the change in the mode of failure is reversed (brittle to ductile) in this study as a consequence of corrosion.

- Corrosion of the beams has not affected the cracking load of the beams, which is almost the same for all the beams (approximately 8 kN).

4.4 AMOUNT OF CORROSION

As explained in section 3.2.7 of Chapter 3, amount of corrosion has been measured using the Gravimetric mass loss method. The length of all tensile bars used in this study has been kept equal to 770 mm. The calculated values are shown in **Table 4.1** below

Table 4.1: Amount of corrosion based on weight loss of tensile bars.

Specimen no.	Description	Average Weight of tensile bars per unit length (before immersion in 3.5% HCl)	Average Weight of tensile bars per unit length (after immersion in 3.5% HCl)	Amount of corrosion (by equation 3.2 of section 3.2.7)
B1	No corrosion, no load	0.879 g/mm	0.8779 g/mm	0%
B2	Corrosion, 25% pre-load	-	0.8623 g/mm	1.77%
B3	Corrosion, 50% pre-load	-	0.8454 g/mm	3.69%
B4	Corrosion, 75% pre-load	-	0.8428 g/mm	3.99%
B5	Corrosion, 50% pre-load, 1% sustained load	-	0.855 g/mm	2.60%

4.4.1 DISCUSSIONS

- The lowest amount of corrosion is for the beam B2 (1.77%) and the highest for the beam B4 (3.99%). After extraction of reinforcement bars, most of the corrosion products surrounding

the steel bars have been found to be green/black in color. This kind of corrosion is known to occur due to large distances between anodic and cathodic regions or due to lack of availability of sufficient oxygen at the level of reinforcement bars. [1]

- The values for amount of corrosion calculated above by the gravimetric weight loss are based on the assumption that corrosion of the reinforcement is uniform throughout the length. This does not reflect the actual corrosion along the length of the tensile reinforcement, especially in case of chlorides, which are known to cause localized ‘pitting’ corrosion of the reinforcement at specific locations (which could be 1-5 times greater than that calculated by gravimetric mass loss) only [30]. Indeed, after extraction of the tensile bars from the corroded beams, evidence of pitting has been found as shown in **Figure 4.8**. This could explain why the beams B3 and B5, having corrosion rates of 3.69% and 2.60% respectively, do not show correspondingly decreasing ultimate load values (137.2 kN for B3 and 135.45 kN for B5).
- In terms of deflections, there has been not found any general increasing or decreasing trend with change in amount of corrosion of the beams.



Figure 4.8: Pitting corrosion in the tensile bars of beam B4

4.5 EFFECT OF SUSTAINED LOAD

- Pre-load level of 50% of the ultimate load capacity of the healthy beam B1 reduced the ultimate load of beam B3 to 95.8% of the beam B1. The combination of 50% pre-load with

1% sustained load while corrosion reduced the load capacity of beam B6 to 94.6% of the ultimate load capacity of beam B1.

- Though the effect of sustained loads has been not investigated in detail and the value of applied sustained load is very low, it is clear from the one case of beam B5 (which has been pre-loaded to 50% and then subjected to 1% sustained load during corrosion) that sustained loading during corrosion has a greater impact on the corrosion related deterioration of structural behavior on the beam. This is due to the reduction in crack-widths upon removal of imposed loads as observed in the case of pre-loaded beams, and as is reported elsewhere in literature [12].

4.6 EFFECT ON STRENGTH OF TENSILE BARS

After the tensile bars are extracted from the beam specimens and after determination of mass loss values, the middle 18 inch (457.2 mm) lengths of the bars are cut out of the 770 mm bars. These 18 inch bar specimens are then tested in tension in the UTM machine as shown in **Figure 4.9** shown below. The grip length is 200 mm and gauge length is kept at 250 mm.



Figure 4.9: Tensile testing of corroded steel bar specimen.

The average ultimate strengths for the tensile bar specimens as obtained from the UTM machine are given in **Table 4.2**

As observed from Table 4.2, for the beams B2, B3, and B4 there is a reduction of 5.9%, 13.6% and 15.7% of the ultimate strength values with respect to the healthy beam B1. Also, for the beam B5, the ultimate stress value is slightly less than that of beam B3.

The reduction in the ultimate strengths varied for the two tensile bars of a single beam. This can be attributed to the uneven corrosion of the two bars caused by the irregular crack patterns induced by the pre-loads.

Table 4.2: Ultimate strengths of tensile reinforcements of the beams

Beam no.	Description	Average ultimate strength of tensile bars (N/mm ²)
B1	No corrosion, no pre-load	659.83
B2	Corrosion, 25% pre-load	620.04
B3	Corrosion, 50% pre-load	570
B4	Corrosion, 75% pre-load	555.76
B5	Corrosion, 50% pre-load, 1% sustained load	567.92

CHAPTER 5

CONCLUSIONS

5.1 CONCLUSIONS

From this experimental study into the effect of pre-loads on accelerated corrosion of beams the following conclusions may be drawn:

- The effect of cracking of cover concrete by means of pre-loading of the beams suggests that the level of pre-load affects corrosion of the beams. Higher level of pre-load leads to a higher corrosion of the steel bars and causes greater loss of strength. Also, pre-loading may increase the likelihood of localized corrosion due to corrosion being favored at locations of cracks along the length of the beam.
- The higher reduction in strength in case of B5 than in B3 indicates that combination of pre-loads with sustained loads as low as 1% of the beam capacity may affect the behavior of the RC beams.
- Corrosion of the beams can change their mode of failure. In this study, the change in the failure mode of the beam has been observed to vary from shear to flexure type.
- The load-carrying capacity decreased with increasing amount of corrosion of the beams, except for the cases of B3 and B5. The gravimetric loss formula assumes uniform corrosion of the bar, which is not the actual scenario. In reality, localized ‘pitting’ is observed which caused localized corrosion of the bars, leading to cross-sectional area reductions in specific locations of the bars only.

5.2 SCOPE FOR FUTURE WORK

This study has been performed using limited resources and a single parameter (pre-load level) with an objective to gain a basic understanding of the corrosion process in the presence of cracks. However, in order to improve this understanding other related aspects need to be studied as well, which are given below:

- The effect of sustained loading on the corrosion process, separately and in combination with pre-loading need to be studied in greater detail.

- Effects of dynamic loads on corrosion, as are present in practical applications (e.g. highway bridges), should be investigated.
- Most structures in everyday use are assumed to be cracked and micro-crack-widths smaller than 0.4 mm are permitted in most codes. A more detailed study on the effect of pre-loads in terms of these crack-widths on aspects of service life of corrosion needs to be performed.
- The study can include more parameters, such as use of different binders (fly ash, silica fume, GGBS) and compare the effects of these in addition to pre-loads and sustained loads. Also, the concrete cover thickness can be varied and its effect on corrosion can be observed.
- The real-time corrosion measurements (half-cell potential, concrete resistivity, ultrasonic pulse velocity etc.) also should be included in the study for better understanding of the corrosion process during exposure to various loading conditions.

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