



Cairo University

**FLEXURAL BEHAVIOR OF TWO-SPAN REINFORCED
CONCRETE BEAMS SUBJECTED TO SELECTED
FACE CORROSION AFTER INITIALLY LOADED _
EXPERIMENTAL AND FINITE ELEMENT**

By

Hassan Ahmed Hassan Ahmed

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY
in
Structural Engineering

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2019

**FLEXURAL BEHAVIOR OF TWO-SPAN REINFORCED
CONCRETE BEAMS SUBJECTED TO SELECTED
FACE CORROSION AFTER INITIALLY LOADED _
EXPERIMENTAL AND FINITE ELEMENT**

By
Hassan Ahmed Hassan Ahmed

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY
in
Structural Engineering

Under the Supervision of

Prof. Dr. Osama Abdel Ghafoor
Hodhod

Prof. Dr. Mohamed Mohsen El-Attar

.....
Professor of Properties and Strength of
Materials
Structural Engineering Department
Faculty of Engineering, Cairo University,
Egypt

.....
Professor of Properties and Strength of
Materials
Structural Engineering Department
Faculty of Engineering, Cairo University,
Egypt

Prof. Dr. Abdel Moneim Yasin Sanad

.....
Professor of Structural Engineering
Construction & Building Department
Faculty of Engineering, Arab Academy for
Science & Technology

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2019

**FLEXURAL BEHAVIOR OF TWO-SPAN REINFORCED
CONCRETE BEAMS SUBJECTED TO SELECTED
FACE CORROSION AFTER INITIALLY LOADED _
EXPERIMENTAL AND FINITE ELEMENT**

By
Hassan Ahmed Hassan Ahmed

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY
in
Structural Engineering

Approved by the
Examining Committee

Prof. Dr. Osama Hodhod, Thesis Main Advisor

Prof. Dr. Mohamed Mohsen El-Attar, Thesis Advisor

Prof. Dr. Abdel Moneim Yasin Sanad, Thesis Advisor

Prof. Dr. Hamed Salem Hadhood, Internal examiner

Prof. Dr. Hatem Hamdy Gheith, External examiner
- Housing & Building National Research Center

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2019

Engineer's Name: Hassan Ahmed Hassan Ahmed
Date of Birth: 03/12/1986
Nationality: Egyptian
E-mail: hassan.ahmed@staff.aast.edu
Phone: +201110553116
Address: New Cairo-First District-No.18
Registration Date: 01/03/2014
Awarding Date: .../.../ 2019
Degree: Doctor of Philosophy
Department: Structural Engineering Department



Supervisors:

Prof. Dr. Osmaa Abdel Ghafoor Hodhod
Prof. Dr. Mohamed Mohsen El-Attar
Prof. Dr. Abdel Moneim Yasin Sanad

Examiners:

Prof. Dr. Osmaa Abdel Ghafoor Hodhod
Prof. Dr. Mohamed Mohsen El-Attar
Prof. Dr. Abdel Moneim Yaseen Sanad
Prof. Dr. Hamed Salem Hadhood
Prof. Dr. Hatem Hamdy Gheith

Title of Thesis:

Flexural Behavior of Two-span Reinforced Concrete Beams Subjected to Selected Face Corrosion After Initially Loaded _ Experimental and Finite Element

Key Words:

ABAQUS; Chlorides; Concrete; Corrosion; Finite Element Analysis; Reinforcement.

Summary:

Corrosion of reinforcement bars in two-span concrete beams was investigated using both experimental and finite element analysis. The experimental program comprised a total of twenty-two full scale reinforced concrete beams. The beams were divided into three equal groups of seven beams each, in addition to a non-corroded control beam. The three groups were initially loaded, before subjecting to corrosion, with a concentrated load at the middle of each span ranging from zero loading for group No. 1, to 40% and 60% of the ultimate load for groups No.2 and No. 3 respectively. The impressed current technique was used for accelerating the corrosion with a current intensity not exceeding 200 $\mu\text{A}/\text{cm}^2$. The tension side at the middle of the beam was selected for corrosion to avoid uniform corrosion of the rebars along the beam. A finite element model was developed using the finite element code ABAQUS 6.14. A new model was proposed to model the behavior of concrete in compression and tension through the plastic portion of the stress-strain curve. The finite element model showed a good agreement with the results of the experimental beams.

Disclaimer

I hereby declare that this thesis is my own original work and that no part of it has been submitted for a degree qualification at any other university or institute.

I further declare that I have appropriately acknowledge all sources used and have cited them in the references section.

Name: Hassan Ahmed Hassan Ahmed

Date: 18/12/2018

Acknowledgments

First ALLAH is praised for the aid and guidance.

The present work was conducted out at the Structural Department, Faculty of Engineering, Cairo University in conjunction with the Construction & Building Department, College of Engineering & Technology, Arab Academy for Science & Technology, Cairo, Egypt.

The author would like to express his deepest gratitude and appreciation to his supervisors Prof. Osama Hodhod, Prof. Mohamed Mohsen El-Attar and Prof. Abdel Moneim Sanad for their continuous advises through the whole research. Their support and valuable remarks were greatly useful and helpful to achieve effective and beneficial results.

The experimental work was carried out at the Arab Academy for Science & Technology, Cairo, Egypt. The great help of the Construction and Building department and the materials laboratory technician “Soliman Mohye” is highly appreciated.

Special thanks for the helpful academic colleagues (Teaching assistants and undergraduate students) for their helpful advice in contributing to the development of this research.

The author would like to send his worm and sincere thanks to his father “Eng. Ahmed Hassan” for his valuable support, assistance, and endless help throughout all stages of the research; including but not limited to: materials supply and preparation. This work would have been insurmountable without his hard work, knowledge and editing skills.

Last, the author would like to express his deep feelings towards each member of his family to whom he owes every success in his life. His cordial thanks spread out to his mother, father, sister, and brother for their love, support and guidance throughout his life and for inculcating in him the passion for knowledge.

Hassan Ahmed Hassan Ahmed
December 2018

Dedication

I dedicate the success in this work to my beloved parents for always supporting me and driving force in my life and enhancing my career. Throughout my life, they have actively supported me in my studies and work. They pushed me towards the right track for success. Many thanks to my father who died while I am working on this research. Without his help and advices, nothing of my experimental work would have been established or finished.

Hassan Ahmed Hassan Ahmed
December 2018

Table of Contents

| | |
|---|-------------|
| ACKNOWLEDGMENTS | I |
| DEDICATION..... | II |
| TABLE OF CONTENTS..... | III |
| LIST OF TABLES | VII |
| LIST OF FIGURES | VIII |
| ABSTRACT | XIV |
| CHAPTER 1 : INTRODUCTION..... | 1 |
| 1.1. BACKGROUND..... | 1 |
| 1.2. DETERIORATION OF REINFORCED CONCRETE STRUCTURES..... | 2 |
| 1.3. MOTIVATION FOR RESEARCH..... | 3 |
| 1.4. OBJECTIVES OF THE THESIS | 5 |
| 1.5. THESIS OUTLINE | 6 |
| CHAPTER 2 : LITERATURE REVIEW..... | 7 |
| 2.1. CONCRETE REINFORCEMENT CORROSION | 7 |
| 2.2. INFLUENCE OF CORROSION ON RC BEAMS' FLEXURAL, SHEAR AND SERVICEABILITY BEHAVIOR | 8 |
| 2.2.1. Influence of corrosion on flexural capacity of RC beams | 8 |
| 2.2.2. Influence of corrosion on shear capacity of RC beams | 11 |
| 2.2.3. Influence of corrosion on serviceability of RC beams | 14 |
| 2.3. LABORATORY ACCELERATED CORROSION TECHNIQUES | 16 |
| 2.3.1. Accelerated depassivation of steel | 16 |
| 2.3.2. Impressed current density | 18 |
| 2.4. DETERMINING THE CHLORIDE DIFFUSION COEFFICIENT | 18 |
| 2.4.1. AASHTO T259: salt ponding test | 19 |
| 2.4.2. Bulk diffusion test: NordTest NTBuild 443 | 19 |
| 2.4.3. AASHTO T277 (ASTM C1202): Electrical indication of concrete's ability to resist chloride ion penetration (Rapid Chloride Permeability Test) | 20 |
| 2.4.4. Electrical migration test | 21 |
| 2.4.5. The rapid migration test (CTH Test) | 21 |
| 2.4.6. Pressure penetration techniques | 22 |
| 2.4.7. Lab sorptivity test | 23 |
| 2.5. ATTEMPTS FOR REPAIRING CORRODED REINFORCED CONCRETE BEAMS | 23 |
| 2.6. INFLUENCE OF NANO-MATERIALS ADDITIONS ON THE LOAD CARRYING CAPACITY OF RC BEAMS | 27 |
| CHAPTER 3 : PROPERTIES OF MATERIALS AND TEST SET-UP..... | 29 |
| 3.1 EXPERIMENTAL WORK PLAN | 29 |
| 3.2 MATERIALS | 31 |
| 3.2.1 Cement | 31 |

| | | |
|-------|---|----|
| 3.2.2 | Steel | 31 |
| 3.2.3 | Concrete Composition | 32 |
| 3.3 | REINFORCED CONCRETE BEAMS PREPARATION..... | 34 |
| 3.4 | COMPRESSIVE STRENGTH RESULTS STATISTICAL ANALYSIS | 38 |
| 3.5 | LOADING FRAMES AND LOADING SET-UP..... | 39 |
| 3.6 | ACCELERATED CORROSION SET-UP..... | 43 |

CHAPTER 4 : DISCUSSION AND ANALYSIS OF CORRODED RC BEAMS..49

| | | |
|----------|--|----|
| 4.1. | TEST SET-UP FOR LOADING THE RC BEAMS | 49 |
| 4.2. | FLEXURAL BEHAVIOR OF THE NON-CORRODED CONTROL BEAM (NC-CB) | 50 |
| 4.2.1. | Crack Patterns | 50 |
| 4.2.2. | Load-deflection relationship | 51 |
| 4.3. | CORROSION READINGS VS. TIME FOR ALL BEAMS | 52 |
| 4.3.1. | Corrosion of the (C-ow) beams | 52 |
| 4.3.2. | Corrosion of the (C-40P) beams | 54 |
| 4.3.3. | Corrosion of the (C-60P) beams | 55 |
| 4.4. | FLEXURAL BEHAVIOR OF CORRODED BEAMS | 57 |
| 4.4.1. | Load-deflection relationship for (C-ow) beams | 57 |
| 4.4.2. | Load-deflection relationship for (C-40P) beams | 59 |
| 4.4.3. | Load-deflection relationship for (C-60P) beams | 60 |
| 4.4.4. | Load-deflection for all beams versus the control beam | 61 |
| 4.5. | BEAMS SUBJECTED TO INCREASED DEGREES OF CORROSION | 62 |
| 4.5.1. | Beams corroded under their own weight only (C-ow) | 62 |
| 4.5.1.1. | C-ow_14 days | 62 |
| 4.5.1.2. | C-ow_28 days | 64 |
| 4.5.1.3. | C-ow_42 days | 65 |
| 4.5.1.4. | C-ow_56 days | 66 |
| 4.5.1.5. | C-ow_70 days | 67 |
| 4.5.1.6. | C-ow_84 days | 69 |
| 4.5.2. | Beams corroded after initially loaded (C-40P) | 70 |
| 4.5.2.1. | C-40P_14 days | 70 |
| 4.5.2.2. | C-40P_28 days | 72 |
| 4.5.2.3. | C-40P_42 days | 73 |
| 4.5.2.4. | C-40P_56 days | 74 |
| 4.5.2.5. | C-40P_70 days | 76 |
| 4.5.2.6. | C-40P_84 days | 77 |
| 4.5.3. | Beams corroded after initially loaded (C-60P) | 79 |
| 4.5.3.1. | C-60P_14 days..... | 79 |
| 4.5.3.2. | C-60P_28 days..... | 81 |
| 4.5.3.3. | C-60P_42 days..... | 82 |
| 4.5.3.4. | C-60P_56 days..... | 83 |
| 4.5.3.5. | C-60P_70 days..... | 84 |
| 4.5.3.6. | C-60P_84 days..... | 86 |
| 4.6. | INFLUENCE OF CORROSION ON BEAMS AT DIFFERENT AGES AND VALUES OF INITIAL LOADING | 87 |
| 4.7. | DETERIORATION OF LOAD CARRYING CAPACITY AND TOTAL ENERGY FOR CORRODED BEAMS | 92 |
| 4.8. | PHYSICAL AND MECHANICAL PROPERTIES OF CORRODED BARS | 95 |
| 4.8.1. | Non-corroded control bar (NC-CB) | 95 |
| 4.8.2. | [C-ow] bar | 96 |

| | |
|---|------------|
| 4.8.3. [C-ow_14] bar | 97 |
| 4.8.4. [C-ow_28] bar | 98 |
| 4.8.5. [C-ow_42] bar | 99 |
| 4.8.6. [C-ow_56] bar | 100 |
| 4.8.7. [C-ow_70] bar | 101 |
| 4.8.8. [C-ow_84] bar | 102 |
| 4.8.9. [C-40P] bar | 103 |
| 4.8.10. [C-40P_14] bar | 104 |
| 4.8.11. [C-40P_28] bar | 105 |
| 4.8.12. [C-40P_42] bar | 106 |
| 4.8.13. [C-40P_56] bar | 107 |
| 4.8.14. [C-40P_70] bar | 108 |
| 4.8.15. [C-40P_84] bar | 109 |
| 4.8.16. [C-60P] bar | 110 |
| 4.8.17. [C-60P_14] bar | 111 |
| 4.8.18. [C-60P_28] bar | 112 |
| 4.8.19. [C-60P_42] bar | 113 |
| 4.8.20. [C-60P_56] bar | 114 |
| 4.8.21. [C-60P_70] bar | 115 |
| 4.8.22. [C-60P_84] bar | 116 |
| 4.8.23. Mass loss for all corroded bars | 117 |
| 4.8.24. Deterioration of load carrying capacities and ductility for corroded bars | 117 |
| 4.9. FAILURE MECHANISM IN CORRODED RC BEAMS..... | 119 |
| CHAPTER 5 : NUMERICAL SIMULATION FOR CORRODED REINFORCED CONCRETE BEAMS | 125 |
| 5.1. BACKGROUND | 125 |
| 5.1.1. Definition of concrete as an elastic-plastic material | 125 |
| 5.1.1.1. Tension stiffening relationship | 126 |
| 5.1.1.2. Compressive stress-strain relationship | 126 |
| 5.1.2. Simulation of corrosion progress in RC beams | 128 |
| 5.2. ELASTIC MODEL FOR THE RC BEAM | 128 |
| 5.2.1. Geometry and elements for the beam and its reinforcement | 128 |
| 5.2.2. Modelling of the supporting and loading plates | 129 |
| 5.2.3. Assembly and interactions between the model components | 130 |
| 5.2.4. Behavior of the elastic model | 131 |
| 5.2.5. Decreasing the size of the model | 133 |
| 5.3. ELASTIC-PLASTIC MODEL FOR THE NC-CB BEAM | 136 |
| 5.3.1. Concrete material definition | 136 |
| 5.3.1.1. Tensile behavior | 136 |
| 5.3.1.2. Compressive behavior | 137 |
| 5.3.1.3. Damage evolution | 138 |
| 5.3.2. Results and discussion of the NC-CB model..... | 140 |
| 5.3.2.1. Load-deflection relationship (NC-CB)..... | 140 |
| 5.3.2.2. Crack patterns (NC-CB)..... | 141 |
| 5.3.2.3. Elements compressive and tensile behavior (NC-CB)..... | 142 |
| 5.4. ELASTIC-PLASTIC MODEL FOR THE CORRODED RC BEAM (C-OW) | 146 |
| 5.4.1. Model geometry | 146 |
| 5.4.2. Concrete material definition for the cracked part | 146 |

| | |
|---|------------|
| 5.4.3. Steel material definition for the cracked part | 148 |
| 5.4.4. Results and discussion of the C-ow model | 148 |
| 5.4.4.1.Load-deflection relationship (C-ow)..... | 149 |
| 5.4.4.2.Crack patterns (C-ow)..... | 151 |
| 5.4.4.3.Elements compressive and tensile behavior (C-ow)..... | 151 |
| 5.5. EFFECT OF STEEL BARS' DETERIORATED PROPERTIES ON THE MODEL BEHAVIOR..... | 152 |
| 5.6. RESULTS FOR THE C-40P AND C-60P FINITE MODEL | 156 |
| 5.7. NEW MODELS FOR THE CONCRETE TENSION-SOFTENING AND REBARS' TENSILE BEHAVIOR..... | 163 |
| CHAPTER 6 : CONCLUSIONS AND RECOMMENDATIONS | 167 |
| 6.1. SUMMARY | 167 |
| 6.2. CONCLUSIONS | 167 |
| 6.3. RECOMMENDATIONS FOR FUTURE WORK..... | 168 |
| REFERENCES..... | 169 |

List of Tables

| | |
|--|-----|
| Table 3.1: Physical and chemical properties for CEM I 42.5 R..... | 31 |
| Table 3.2: Concrete mixes proportioning and strength results (MPa)..... | 32 |
| Table 4.1: Deterioration percentages in ultimate load and total energy for corroded beams | 94 |
| Table 5.1: Average material properties for concrete | 136 |
| Table 5.2: Damage parameters values in compression, d_c , and tension, d_t | 139 |
| Table 5.3: Average material properties for the longitudinal and shear reinforcement bars | 139 |
| Table 5.4: Damage parameters and cracking strain values in tension, d_t , for the cracked concrete..... | 147 |

List of Figures

| | |
|--|----|
| Figure 1.1: Service life of concrete infrastructure [7] | 3 |
| Figure 1.2: Collapse of a pedestrian bridge in the U.S. [71] | 3 |
| Figure 1.3: Collapse of buildings in Northwest Ecuador [72]..... | 4 |
| Figure 1.4: Examples of deteriorated RC buildings in Alexandria, Egypt..... | 5 |
| Figure 2.1: Corrosion cell in reinforced concrete [14] | 7 |
| Figure 2.2: Specimens detailing for groups A to C (left); Accelerated corrosion set-up (right) [23] | 9 |
| Figure 2.3: The load-deflection curves for the corroded RC beams [23]..... | 10 |
| Figure 2.4: Anchorage of steel bar: (a) straight bar, (b) hooked bar, (c) hooked bar, (d) headed bar, and (e) welded bar [24] | 10 |
| Figure 2.5: Resisting mechanisms in bond-slip relationship [26] | 11 |
| Figure 2.6: Transfer of effective bond force: (a) before transfer, and (b) after transfer [24] | 11 |
| Figure 2.7: Beam details and test set-up (units: mm) [27] | 12 |
| Figure 2.8: Accelerated corrosion process [27]..... | 12 |
| Figure 2.9: Load deflection curves: (a) Group A beams; (b) Group B beams; (c) Comparison between Groups A and B [27] | 13 |
| Figure 2.10: Layout pf beams belonging to group B (units: mm) [18] | 14 |
| Figure 2.11: Loading system and chloride environment [18] | 15 |
| Figure 2.12: Chloride profile at the depth of reinforcement (16 mm) of Group B beams [18] | 15 |
| Figure 2.13: Different factors of serviceability limit states of the beams [18]..... | 16 |
| Figure 2.14: Transverse and vertical strains before concrete cover cracking [38]..... | 17 |
| Figure 2.15: AASHTO T259 _ Salt Ponding Test setup [12] | 19 |
| Figure 2.16: AASHTO T259 _ Salt Ponding Test setup [12] | 20 |
| Figure 2.17: AASHTO T277 (ASTM C1202) test setup [12]..... | 20 |
| Figure 2.18: Chloride Migration Cell [12] | 21 |
| Figure 2.19: Rapid Migration Cell [12]..... | 22 |
| Figure 2.20: Pressure Penetration Test [12] | 22 |
| Figure 2.21: Lab Sorptivity Technique [12]..... | 23 |
| Figure 2.22: Typical specimen dimensions and reinforcement detailing [45] | 24 |
| Figure 2.23: Load-deflection relationship of corroded specimens with non-corroded specimen (NCB-1) [45] | 24 |
| Figure 2.24: Load-deflection relationship of specimens repaired with polymer-modified mortar in comparison with non-corroded specimen (NCB-1) [45] | 25 |
| Figure 2.25: Load-deflection relationship of specimens repaired with epoxy-based repair material in comparison with non-corroded specimen (NCB-1) [45] | 25 |
| Figure 2.26: Specimen test set-up and the reinforcement configuration. [49] | 26 |
| Figure 2.27: Crack pattern of a corroded beam after the end of the accelerated corrosion. [49] | 27 |
| Figure 2.28: Load-displacement curves for ‘shear’ beams. [58]..... | 28 |
| Figure 2.29: Load-displacement curves for ‘bending’ beams [58] | 28 |
| Figure 3.1: Experimental work master plan | 30 |
| Figure 3.2: Longitudinal and shear reinforcement bars..... | 32 |
| Figure 3.3a: BS_EN 206 concrete cubes | 33 |
| Figure 3.3b: ECP 203 concrete cubes..... | 33 |
| Figure 3.3c: ACI 318R-08 concrete cubes | 33 |

| | |
|---|----|
| Figure 3.4: Typical beam dimensions (mm) and reinforcement detailing | 34 |
| Figure 3.5: Preparation of longitudinal and shear reinforcement before casting | 35 |
| Figure 3.6: Fabrication of the wooden forms for casting the RC beams..... | 35 |
| Figure 3.7: Wooden forms sprayed with WOOD SURV | 36 |
| Figure 3.8: Assembly of the wooden forms and the reinforcement bars..... | 36 |
| Figure 3.9: Coarse aggregate washing before mixing | 37 |
| Figure 3.10: Concrete placing, compaction, and leveling | 37 |
| Figure 3.11: Forms removal and curing of concrete beams | 38 |
| Figure 3.12: Statistical analysis of individual strength test for 22 Beams | 38 |
| Figure 3.13: Moving average for each three successive results | 39 |
| Figure 3.14: Two-span beams loaded by their own weight only | 39 |
| Figure 3.15: Schematic drawing for the steel loading frame..... | 40 |
| Figure 3.16: Assembly of the steel frames | 41 |
| Figure 3.17: Loading of the beams on the steel frames..... | 42 |
| Figure 3.18: The two frames fully loaded by the beams | 42 |
| Figure 3.19: Loading the beams using the hydraulic and screw jacks | 43 |
| Figure 3.20: Location of the cathodic bar in the RC beam | 44 |
| Figure 3.21: Schematic drawing showing the electric circuit set-up for the accelerated corrosion process | 45 |
| Figure 3.22: The three groups of beams connected by the copper electric wires | 46 |
| Figure 3.23: Acrylic ponds fixed on the middle upper faces of the beams | 47 |
| Figure 3.24: Cycles of drying (3 days) left and wetting (4 days) right | 47 |
| Figure 3.25: DC lab switching mode power supply | 48 |
| Figure 3.26: Isolation of the upper portion of the stirrups by isolated electric tapes | 48 |
| Figure 4.1: Typical beam loaded on the loading frame..... | 49 |
| Figure 4.2: Two hydraulic jacks fixed at the loading points at the middle of each span | 50 |
| Figure 4.3: Fixation of the LVDT on the leveled welded bars..... | 50 |
| Figure 4.4: Development of cracks at the critical sections during testing (NC-CB)..... | 51 |
| Figure 4.5: Load-deflection curves for the (NC-CB) in flexural test | 52 |
| Figure 4.6: Corrosion readings (volt) vs. Duration (days) for the (C-ow) beams | 53 |
| Figure 4.7: (C-ow) beams before corrosion (left); and after corrosion (right)..... | 53 |
| Figure 4.8: Corrosion readings (volt) vs. Duration (days) for the (C-40P) beams..... | 54 |
| Figure 4.9: Corrosion products appearance on the surface of the (C-40P) beams | 54 |
| Figure 4.10: Corrosion readings (volt) vs. Duration (days) for the (C-60P) beams..... | 55 |
| Figure 4.11: Corrosion products appearance on the surface of the (C-60P) beams | 55 |
| Figure 4.12: Crack at the contaminated face of a (C-60P) beam | 56 |
| Figure 4.13: Corrosion readings vs. duration for the average of each group of the three groups | 57 |
| Figure 4.14: Load-deflection curve for the (C-ow) beam in flexural test | 58 |
| Figure 4.15: The cracks pattern for the (C-ow) after failure in a flexural test | 58 |
| Figure 4.16: Load-deflection curve for the (C-40P) beam in flexural test..... | 59 |
| Figure 4.17: The cracks pattern for the (C-40P) after failure in a flexural test..... | 59 |
| Figure 4.18: Load-deflection curve for the (C-60P) beam in flexural test..... | 60 |
| Figure 4.19: The cracks pattern for the (C-60P) after failure in a flexural test..... | 60 |
| Figure 4.20: Load-deflection curves for the corroded beams (C-ow), (C-40P), (C-60P) with the control beam (NC-CB) | 61 |
| Figure 4.21: Cracking patterns for the C-ow_14 beam at the contaminated section | 62 |
| Figure 4.22: Cracking patterns for the C-ow_14 beam at the +ve moment sections | 63 |
| Figure 4.23: Load-deflection relationship for the C-ow_14 beam | 63 |
| Figure 4.24: Cracking patterns for the C-ow_28 beam | 64 |
| Figure 4.25: Load-deflection relationship for the C-ow_28 beam | 64 |

| | |
|---|----|
| Figure 4.26: Cracking patterns for the C-ow_42 beam | 65 |
| Figure 4.27: Load-deflection relationship for the C-ow_42 beam | 66 |
| Figure 4.30: Corrosion and flexural cracks for the C-ow_70 beam at the contaminated section..... | 67 |
| Figure 4.32: Load-deflection relationship for the C-ow_70 beam | 68 |
| Figure 4.36: Cracking patterns for the C-40P_14 beam at the contaminated section | 70 |
| Figure 4.37: Cracking patterns for the C-40P_14 beam at the +ve moment sections | 71 |
| Figure 4.38: Load-deflection relationship for the C-40P_14 beam..... | 71 |
| Figure 4.39: Cracking patterns for the C-40P_28 beam..... | 72 |
| Figure 4.40: Load-deflection relationship for the C-40P_28 beam..... | 72 |
| Figure 4.41: Cracking patterns for the C-40P_42 beam..... | 73 |
| Figure 4.42: Failure mode for the C-40P_42 beam..... | 73 |
| Figure 4.43: Load-deflection relationship for the C-40P_42 beam..... | 74 |
| Figure 4.44: Cracking patterns for the C-40P_56 beam contaminated section..... | 74 |
| Figure 4.45: Cracking patterns for the C-40P_56 beam positive sections | 75 |
| Figure 4.47: Corrosion and flexural cracks for the C-40P_70 beam at the contaminated section..... | 76 |
| Figure 4.48: Flexural cracks for the C-40P_70 beam at the +ve moment sections..... | 76 |
| Figure 4.49: Load-deflection relationship for the C-40P_70 beam..... | 77 |
| Figure 4.53: Cracking patterns for the C-60P_14 beam at the contaminated section | 79 |
| Figure 4.54: Cracking patterns for the C-60P_14 beam at the +ve moment sections | 80 |
| Figure 4.55: Load-deflection relationship for the C-60P_14 beam..... | 80 |
| Figure 4.56: Cracking patterns for the C-60P_28 beam..... | 81 |
| Figure 4.57: Load-deflection relationship for the C-60P_28 beam..... | 81 |
| Figure 4.58 Cracking patterns for the C-60P_42 beam..... | 82 |
| Figure 4.59: Failure mode for the C-60P_42 beam..... | 82 |
| Figure 4.60: Load-deflection relationship for the C-60P_42 beam..... | 83 |
| Figure 4.61: Corrosion and pre-loading cracks for the C-60P_56 beam at the contaminated section (left) and the positive section (right) | 83 |
| Figure 4.62: Cracking patterns and failure mode for the C-60P_56 beam..... | 84 |
| Figure 4.63: Load-deflection relationship for the C-60P_56 beam..... | 84 |
| Figure 4.64: Corrosion and flexural cracks for the C-60P_70 beam at the contaminated section..... | 85 |
| Figure 4.65: Load-deflection relationship for the C-60P_70 beam..... | 85 |
| Figure 4.67: Flexural cracks for the C-60P_84 beam at the +ve moment sections..... | 86 |
| Figure 4.68: Load-deflection relationship for the C-60P_84 beam..... | 87 |
| Figure 4.69: Load-deflection relationship for the C-ow beams at different ages..... | 88 |
| Figure 4.70: Load-deflection relationship for the C-40P beams at different ages | 88 |
| Figure 4.71: Load-deflection relationship for the C-60P beams at different ages | 89 |
| Figure 4.72: Load-deflection relationship for the all beams at 14 days after the first symptoms of corrosion | 89 |
| Figure 4.73: Load-deflection relationship for the all beams at 28 days after the first symptoms of corrosion | 90 |
| Figure 4.74: Load-deflection relationship for the all beams at 42 days after the first symptoms of corrosion | 90 |
| Figure 4.75: Load-deflection relationship for the all beams at 56 days after the first symptoms of corrosion | 91 |
| Figure 4.76: Load-deflection relationship for the all beams at 70 days after the first symptoms of corrosion | 91 |
| Figure 4.77: Load-deflection relationship for the all beams at 84 days after the first symptoms of corrosion | 92 |