



Cairo University

**BEHAVIOR EVALUATION OF PRESTRESSED CONCRETE BEAM UNDER
CORROSION EXPOSURE**

BY

Mohamed Sayed Mohamed Moawad

A Thesis Submitted to
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

2016

**BEHAVIOR EVALUATION OF PRESTRESSED CONCRETE BEAM UNDER
CORROSION EXPOSURE**

BY

Mohamed Sayed Mohamed Moawad

A Thesis Submitted to
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

2016

**BEHAVIOR EVALUATION OF PRESTRESSED CONCRETE BEAM UNDER
CORROSION EXPOSURE**

BY

Mohamed Sayed Mohamed Moawad

A Thesis Submitted to
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. Ashraf Hassan EL-Zanaty

Professor of Concrete Structures
Structural Engineering Department
Cairo University

Prof. Dr. Hossam Zakeria EL-karmoty

Professor of Strength of Materials
and Quality Control
Housing and Building National
Research Center

FACULTY OF ENGINEERING, CAIRO UNIVERSITY

GIZA, EGYPT

2016

**BEHAVIOR EVALUATION OF PRESTRESSED CONCRETE BEAM UNDER
CORROSION EXPOSURE**

BY

Mohamed Sayed Mohamed Moawad

A Thesis Submitted to

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. Ashraf Hassan EL-Zanaty

Professor of Concrete Structures,

Faculty of Engineering - Cairo University

.....

Prof. Dr. Hossam Zakaria EL-karmoty

Professor of Strength of Materials and Quality Control,

Housing and Building National Research Center

.....

Prof. Dr. Mohamed EL-Saied Issa

Professor of Concrete Structures,

Faculty of Engineering - Cairo University

.....

Prof. Dr. Mohamed Ahmed Khafaga

Professor of Properties and Strength of Materials,

Housing and Building National Research Center

.....

FACULTY OF ENGINEERING, CAIRO UNIVERSITY

GIZA, EGYPT

2016

Engineer: Mohamed Sayed Mohamed Moawad
Date of Birth : 29 /09/1983
Nationality : Egyptian
E-mail : msmmah83@yahoo.com
Phone. : +201025718741
Address : 6 EL-Ashmawy st., EL-Mostashfa st.
EL-Haram, Giza, Egypt
Registration Date : 1/10 /2010
Awarding Date : / /
Degree : Doctor of Philosophy
Department : Structural engineering



Supervisors : Prof. Dr. Ashraf Hassan EL-Zanaty
Prof. Dr. Hossam Zakaria EL-Karmoty

Examiners : Prof. Dr. Mohamed Ahmed Khafaga (External examiner)
Housing and Building National Research Center
Prof. Dr. Mohamed EL-Saied Issa (Internal examiner)
Cairo University
Prof. Dr. Ashraf Hassan EL-Zanaty (Thesis main advisor)
Prof. Dr. Hossam Zakaria EL-Karmoty (Member)

Title of Thesis:

BEHAVIOR EVALUATION OF PRESTRESSED CONCRETE BEAM UNDER CORROSION EXPOSURE

Key Words:

Partially prestressed, Fully prestressed, Corrosion, High strength concrete

Summary:

The main objective of this investigation is to study the behavior of statically determinate prestressed concrete beams subjected to corrosion. The various parameters included the concrete compressive strength, corrosion location effect, prestressing Level, and corrosion exposure effect were investigated. In this respect, an experimental and analytical investigation was conducted on a number of medium scale bonded post-tensioned concrete girders subjected to corrosion. The experimental program consisted of testing eleven beams, six of which were partially bonded prestressed, three beams fully bonded prestressed and the remaining two beams are traditional beams. The beams had an overall width, depth and length 150, 400 and 4500mm respectively. Analytical investigation based on strain compatibility approach was used to predict the deformational behavior of the tested prestressed concrete beams before and after corrosion exposure. Comparison between theoretical and experimental test results was carried out. A very good correlation between the predicted and measured behavior was observed.

ACKNOWLEDGMENT

First of all, I am extremely grateful to **ALLAH** for without his help this work would never have been accomplished.

I would like to express my deepest gratitude and appreciation to Professor **Dr. ASHRAF EL-ZANATY** for his continuous advice throughout this the whole research, great support, valuable remarks, and for his reviewing the manuscript.

My sincere thanks and appreciation to Professor **Dr. HOSSAM ZAKARIA EL-KARMOTY** for his direct supervision, encouragement, great support, valuable remarks, technical assistance and for his patience in reviewing the manuscript.

I would also wish to record my special appreciation and gratitude to my advisor, **Dr. ANWAR MAHMOUD** for his valuable guidance, helpful suggestions, continuous support, and his encouragement through all this work.

I also wish to express my thanks to Professor **Dr. AHMED MEDHAT, and ENG. AHMED EL-KASRAWY** for their help throughout the work.

The experimental work was carried out at Housing and Building National Research Center Laboratories. The great help of the laboratory technical staff was highly appreciated.

DEDICATION

I would like to dedicate this thesis to my wonderful **MOTHER, FATHER**, and my great **WIFE** for their continuous support and everything they have done for me.

ABSTRACT

Prestressed concrete is widely used in the construction industry in buildings, bridges, towers, pressure vessels and offshore structures in numerous structures. The architectural requirements prescribe the incorporation of long span and slender elements in which the prestressed concrete is rendered the most feasible design alternative. The strength and serviceability of reinforced concrete (R.C) and prestressed concrete (P.C) elements are generally affected after corrosion exposure. The basic design objective for such elements would be life safety and collapse prevention.

The main objective of this investigation is to study the behavior of statically determinate prestressed concrete beams subjected to corrosion. In this respect, an extensive experimental and analytical investigation was conducted on number of medium scale bonded post-tension concrete girders subjected to corrosion.

The experimental program consisted of testing eleven beams, six of which were partially bonded prestressed, three beams were fully bonded prestressed and the remaining two beams are non prestressed beams. The beams had an overall width, depth and length 150, 400 and 4500mm respectively. The beams were simply supported with a clear span of 4200mm. The prestressing strand had a harped profile similar to the shape of the applied bending moment. All prestressing specimens were cast using bonded prestressing strands. The strands were stressed after the concrete had reached an age of 28 days, and then grouted with cementitious grout. The beams were tested using two concentrated loads at one-third and twice-third of span by two hydraulic jacks. The previously described set-up was provided with a corrosion located along span of beam. The beams were tested up to failure using a stroke control system after corrosion effect. The studied parameters included corrosion exposure effect, prestressing level, concrete compressive strength, and corrosion location effect. The modes of failure, ultimate load carrying capacity, deflection and strain of steel reinforcement at critical sections were monitored.

The cracking behavior of prestressed and non prestressed concrete beams was presented. Analyses and comparisons of the experimental test result were also introduced. Analytical investigation based on strain compatibility approach was used to predict the deformational behavior of the fully and partially prestressed concrete beams before and after corrosion exposure. Comparison between theoretical and experimental test results was also introduced and showed a reasonable agreement.

Table of Contents

ACKNOWLEDGMENT	I
DEDICATION	II
ABSTRACT	III
Chapter 1: Introduction	
1.1 General	1
1.2 Objectives	1
1.3 Methodology	2
1.4 Preview	2
Chapter 2: Literature Review	
2.1 Serviceability of prestressed concrete	4
2.1.1 Historical of prestress system	4
2.1.2 Definition of prestressed	4
2.1.3 Systems of prestressed	5
2.1.4 Partially and fully prestressed concrete member	5
2.1.5 Nature of concrete steel interface for bonded tendon	8
2.1.6 Properties of materials	9
2.1.6.1 Concrete	9
2.1.6.2 Grouting properties	10
2.1.6.3 Reinforcement	10
2.1.7 Losses in prestressing system	11
2.1.8 Anchorage zone in post tension	11
2.1.9 Behavior of prestressed beams	12
2.1.9.1 Behavior of prestressed beams in flexural	12
2.1.9.2 Serviceability limit states	12
2.1.9.2.1 General	12
2.1.9.2.2 Typical load deflection curve for Prestressed beams	16
2.1.9.3 Tension stiffening	16
2.1.9.4 Crack control	17
2.1.9.5 Ductility calculation	18
2.2 Construction deterioration subject to corrosion exposure	20
2.2.1 Corrosion definition	20
2.2.2 Corrosion process	22
2.2.3 Causes and sources of corrosion	22
2.2.3.1 Carbonation	23
2.2.3.2 Chloride Attack	24
2.2.4 Previous researchs of the corroded reinforced concrete structural elements subject to failure load	25
2.2.4.1 Corrosion in reinforced concrete columns	25
2.2.4.2 Corrosion in reinforced concrete frames	26
2.2.4.3 Corrosion in reinforced concrete beams	26
2.2.5 Deterioration and performance of prestressed steel under corrosion exposure	29
2.2.6 Corrosion effect on the prestressed concrete member	31
2.2.7 Protection of bonded post tensioned system against corrosion in new construction	31
2.2.7.1 Corrosion controlling phenomena in prestressed concrete structure	31

2.2.7.2	Prestressing steel protection	32
2.2.7.3	Duct protection	33
2.2.7.4	Cement grout	34
2.2.7.5	Anchorage protection	34
2.2.8	Field evaluation for post tensioned system	34
Chapter 3: Experimental Program		
3.1	Introduction	37
3.2	Tested specimens	37
3.3	Materials properties	46
3.3.1	Cement	46
3.3.2	Silica fume	46
3.3.3	Admixtures	46
3.3.4	Water	46
3.3.5	Fine aggregate	46
3.3.6	Coarse aggregate	47
3.3.7	Reinforcing steel and prestressing strand	48
3.4	Fabrication of test specimens	48
3.4.1	Concrete mix	49
3.4.2	Installation of prestressing fittings	50
3.4.3	Anchorage zone details	51
3.4.4	Casting of specimens	51
3.4.5	Application of prestressing force	52
3.4.6	Grouting procedure	53
3.5	Accelerated corrosion setup	55
3.6	Mapping of corrosion-induced cracks and spalls	58
3.7	Test Set-Up	61
3.7.1	Loading apparatus	61
3.7.2	Strain measurements	61
3.7.3	Termination of loading	63
3.8	Cross sectional areas measurements of the corroded rebar	63
Chapter 4: Experimental Program Results		
4.1	Introduction	65
4.2	Failure modes	65
4.3	Test results	65
4.3.1	General	65
4.3.2	Specimens behavior	68
4.3.2.1	Specimen B1	68
4.3.2.2	Specimen B2	71
4.3.2.3	Specimen B3	74
4.3.2.4	Specimen B4	76
4.3.2.5	Specimen B5	80
4.3.2.6	Specimen B6	84
4.3.2.7	Specimen B7	87
4.3.2.8	Specimen B8	90
4.3.2.9	Specimen B9	92
4.3.2.10	Specimen B10	95
4.3.2.11	Specimen B11	98
Chapter 5: Experimental Program Results Discussion		
5.1	Introduction	102

5.2	Analysis and discussion of the experimental results	102
5.2.1	General	102
5.2.2	Crack patterns and modes of failure	105
5.2.2.1	Control beams	105
5.2.2.2	Beams subjected to corrosion	107
5.2.3	Load-Deflection and strain behavior	110
5.3	Parameters studies and discussion	111
5.3.1	Corrosion exposure effect on the behavior of the partially prestressed concrete beams, the fully prestressed concrete beams, and the traditional concrete beams against corrosion exposure	111
5.3.1.1	Corrosion exposure effect on the behavior of the partially prestressed concrete beam with 40MPa compressive strength	111
5.3.1.2	Corrosion exposure effect on the behavior of the fully prestressed concrete beam with 40MPa compressive strength	114
5.3.1.3	Corrosion exposure effect on the behavior of the partially prestressed concrete beam with 80MPa compressive strength	117
5.3.1.4	Corrosion exposure effect on the behavior of the traditional concrete beams with 40MPa compressive strength.	119
5.3.2	Prestressed level effect on the behavior of the partially prestressed concrete beams, the fully prestressed concrete beams, and the traditional concrete beams	123
5.3.2.1	Prestressed level effect on the behavior of the non-corroded beams with 40MPa compressive strength	123
5.3.2.2	Prestressed level effect on the behavior of the Corroded beams with 40MPa compressive strength	126
5.3.3	Compressive strength effect on the behavior of the partially prestressed concrete beams with compressive strength 40MPa and 80MPa	129
5.3.3.1	Compressive strength effect on the behavior of the non-corroded partially prestressed concrete beams (B2 and B9)	129
5.3.3.2	Compressive strength effect on the behavior of the partially prestressed concrete beams with fully exposed to corrosion (B5, and B10)	131
5.3.3.3	Compressive strength effect on the behavior of the partially prestressed concrete beams with partially exposed to corrosion (B7, and B11)	135
5.3.4	Corrosion exposure location effect on the behavior of the partially/fully prestressed concrete beams	138
5.3.4.1	Corrosion exposure location effect on the behavior of the partially prestressed concrete beam with 40MPa compressive strength	138
5.3.4.2	Corrosion exposure location effect on the behavior of the fully prestressed concrete beam with 40MPa compressive strength	141
5.3.4.3	Corrosion exposure location effect on the behavior of the partially prestressed concrete beam with 80MPa compressive strength	142
Chapter 6: Analytical Investigation		
6.1	Introduction	146
6.2	material modeling	146
6.2.1	Concrete	146
6.2.2	Steel reinforcement	147

6.2.3	Prestressing steel	147
6.3	Prestressing calculation	148
6.3.1	Losses calculation	148
6.3.2	Prestressing force and extension measurements	150
6.4	Internal forces calculations	153
6.5	site investigation and measurements	155
6.6	Calculation of Moment-Curvature relationship	156
6.7	Deflection prediction	158
6.8	Comparison between the theoretical and experimental load deflection curve	161
6.8.1	Control beams	161
6.8.2	Beams exposed to corrosion	163
Chapter 7: Summery, Conclusion, and Recommendations		
7.1	Summary	170
7.2	Conclusion	170
7.3	Recommendations for future work	172
Reference		173

List of Tables

Table (2.1): Values of modulus of elasticity adopted from (CP110:1972)	10
Table (2.2): Modulus of elasticity and passion's ratio of concrete (Din-5227)	10
Table (2.3): Maximum allowable computed deflection recommended by ACI and CSA code	14
Table (2.4): Maximum recommended crack width (CPCI Metric design manual)	15
Table (2.5): Equations for mechanical properties of corroded rebar (Lee et al, 1999)	27
Table (3.1): Details of tested beams	38
Table (3.2): Mechanical properties of 10mm steel bars	48
Table (3.3): Mechanical properties of prestressing strand	48
Table (3.4): Mix design proportions	49
Table (3.5): Average compressive strength of concrete cubes for test specimens	49
Table (4.1): Experimental results of tested beams	70
Table (5.1): Parameters and group number	103
Table (5.2): Value of Loads, deflections and slope of load-deflection curve at initial stage and post crack stage of beams B2 and B5	112
Table (5.3): Value of Loads, deflections and slope of load-deflection curve at initial stage and post crack stage of beams B3 and B6	115
Table (5.4): Value of Loads, deflections and slope of load-deflection curve at initial stage and post crack stage of beams B9 and B10	117
Table (5.5): Value of Loads, deflections and slope of load-deflection curve at initial stage and post crack stage of beams B1 and B4	120
Table (5.6): Summarized reduction values of the parameter studied	123
Table (5.7): Value of loads, deflections and slope of load-deflection curve at initial stage and post crack stage of beams B1, B2, and B3	124
Table (5.8): Value of loads, deflections and slope of load-deflection curve at initial stage and post crack stage of beams B4, B5, and B6	127
Table (5.9): Value of loads, deflections and slope of load-deflection curve at Initial stage and post crack stage of beams B2 and B9	130
Table (5.10): Value of loads, deflections and slope of load-deflection curve at initial stage and post crack stage of beams B5 and B10	132
Table (5.11): the estimated minimum cross sectional area of beams B5 and B10	132
Table (5.12): Effect of compressive strength on the results of corroded partially prestressed concrete beams B5 and B10	133
Table (5.13): average corrosion induced cracking widthon the bottom and the side of the corroded partially prestressed concrete beams B5 and B10	133
Table (5.14): Value of loads, deflections and slope of load-deflection curve at initial stage and post crack stage for B7 and B11	135
Table (5.15): the estimated minimum cross sectional area of beams B7 and B11	136
Table (5.16): Effect of compressive strength on the results of corroded partially prestressed concrete beams B7 and B11	136
Table (5.17): probable minimum cross sectional area of each corroded rebar of	

corroded partially prestressed concrete beams B7 and B11	136
Table (5.18): Value of loads, deflections and slope of load-deflection curve at initial stage and post crack stage of beams B2, B5, and B11	139
Table (5.19): Value of loads, deflections and slope of load-deflection curve at initial stage and post crack stage of beams B3, B6, and B8	141
Table (5.20): Value of loads, deflections and slope of load-deflection curve at initial stage and post crack stage of beams B9, B10, and B11	143
Table(6.1): Prestressed force after friction losses for partially prestressed concrete beam	149
Table (6.2): Prestressed force after friction losses for fully prestressed concrete beam	149
Table (6.3): Jacking force, initial prestressing force and extension value for calculated and experimental results	150
Table (6.4): Probable minimum cross sectional area of each corroded rebar based on EL-Hefnawy statistical approach	156
Table (6.5): Comparison between the predicted and measured ultimate moment results of the control beams	158
Table (6.6): Comparison between the predicted and measured ultimate moment results of the fired beams	158

List of Figures

Figure (2.1): Stress-strain relationship for prestressing reinforcing (Ghoneim, et al., 2008)	11
Figure (2.2): Idealized load-deflection curves for beams with varying amount of prestressed force (Nilson, 1987)	12
Figure (2.3): Sketch of moment-deflection relationship of internally prestressed concrete beam (Gallab, 2001)	16
Figure (2.4): Typical effect of the effective Prestressed on ultimate and yield curvatures for rectangular section (Naaman et al., 1986)	18
Figure (2.5): Examples of variation of curvature ductility as a function of PPR (Naaman et al., 1986)	18
Figure (2.6): Typical Load-Deflection curves for fully prestressed Beams (Harajli 1985)	19
Figure (2.7): Typical Load-Deflection curves for partially prestressed (Harajli 1985)	20
Figure (2.8): Schematic diagram of the electrochemical processes occurring during corrosion (Glass, 2003)	21
Figure (2.9): Expansive corrosion products on steel (Glass, 2003)	21
Figure (2.10): Corrosion of a concrete beam which has resulted in a crack in the concrete cover following the line of the reinforcement (Glass, 2003)	21
Figure (2.11): The anodic and cathodic reactions (Bamforth et al., 1997)	22
Figure (2.12): Steel corrosion rate as a function of chloride content and relative humidity in carbonated OPC mortar (Glass et al., 1991)	23
Figure (2.13): Suggested procedure for assessing the risk of crack-induced corrosion (BRE, 2001)	36
Figure (3.1): Concrete dimensions of tested beams	39
Figure (3.2): Stirrups distribution along beam length	40
Figure (3.3): Prestressed duct profile for 25mm concrete cover	41
Figure (3.4): Reinforcement details of partially prestressed concrete beams	43
Figure (3.5): Photo of partially prestressed concrete beam	43
Figure (3.6): Reinforcement details of fully prestressed concrete beams	44
Figure (3.7): Photo of fully prestressed concrete beam	44
Figure (3.8): Reinforcement details of traditional concrete beams	45
Figure (3.9): Photo of traditional concrete beam	45
Figure (3.10): Grading of fine aggregate	47
Figure (3.11): Grading of coarse aggregate	47
Figure (3.12): Installing strand as design profile	50
Figure (3.13): Installing grouting fitting into duct	50
Figure (3.14): Details of beam after insulation strand duct and grout fitting	51
Figure (3.15): Anchor zone reinforcement details	51
Figure (3.16): Casted concrete beams	52
Figure (3.17): Prestressing wires procedure	53
Figure (3.18): Grouting pumping procedure	54
Figure (3.19): Placing grout into strand duct	54
Figure (3.20): Grout comes out from the ends of beams during the grout pumping process	55
Figure (3.21): Drainage system that keep the media wet for transporting the electrical field in the samples	56
Figure (3.22): The connection method for prestressed steel to DC. power supply to accelerated corrosion in prestressed steel	56