Ain Shams University
Faculty of Engineering
Structural Department

BOND CHARACTERISTICS OF SELF CONSOLIDATING REINFORCED CONCRETE BEAMS

By

Mohamed Omar El Sawy
B.Sc. Civil Engineering
Ain Shams University, 2000

A Thesis

Submitted in Partial Fulfillment for Requirement of the Degree of the
Master of Science in Structural Engineering

Supervisors

Prof. Dr. Amr Ali Abd Al Rahman
Professor of Concrete Structures
Faculty of Engineering
Ain Shams University

Prof. Dr. Tarek Kamal Hassan
Professor of Concrete Structures
Faculty of Engineering
Ain Shams University

March 2013

Ain Shams University
Faculty of Engineering
Structural Department

BOND CHARACTERISTICS OF SELF CONSOLIDATING REINFORCED CONCRETE BEAMS

By

Mohamed Omar El Sawy
B.Sc. Civil Engineering
Ain Shams University, 2000

A Thesis

Submitted in Partial Fulfillment for Requirement of the Degree of the Master of Science in Structural Engineering

Approved by

Prof. Dr. Amr Ali Abd Al Rahman

Prof. Dr. Tarek Kamal Hassan

Statement

This thesis is submitted to Ain Shams University, Cairo, Egypt, on March 2013 for the degree of Master of Science in Civil Engineering (Structural).

No part of this thesis has been submitted for a degree or qualification at any other University or Institute.

Date : 20 /03 / 2013

Name : Mohamed Omar El Sawy

Signature :

Ain Shams University
Faculty of Engineering
Structural Department

Approval Sheet

Thesis	:	Master of Science in Civil Engineering (Structural)
Student Name	:	Mohamed Omar El Sawy Mohamed
Thesis Title	:	Bond characteristics of self-consolidating reinforced concrete beams

Examiners Committee: **Signature**

Prof. Dr. Adel Al Atar

Professor of Concrete Structures,

Faculty of Engineering

Cairo University

Prof. Dr. Ali Sherif Abd Al Faiad

Professor of Concrete Structures,

Faculty of Engineering

Ain Shams University

Prof. Dr. Amr Ali Abd Al Rahman

Professor of Concrete Structures,

Faculty of Engineering

Ain Shams University

Prof. Dr. Tarek Kamal Hassan

Professor of Concrete Structures,

Faculty of Engineering

Ain Shams University

Information about the Researcher

Name	:	Mohamed Omar El Sawy Mohamed
Date of Birth	:	January 18th, 1978
Place of Birth	:	Cairo, Egypt
Qualifications	:	B.Sc. Degree in Civil Engineering (Structural Eng.) Faculty of Engineering, Ain Shams University (2000)
Present Job	:	Senior Structural Engineer, Dar Al-Handasah Consultants, Cairo, Egypt.
Signature	:	

Acknowledgement

I would like to thank God, without Him, nothing would be possible.

I would like to thank my parents, my brother Yasser Omar El Sawy for their unwavering support and love.

I would like to thank Prof. Dr. Amr Abd Al Rahman Ali and Prof. Dr. Tarek Kamal Hassan for their valuable guidance throughout the years; it is greatly appreciated and will never be forgotten.

I would like to thank **CEMEX READY MIX (Egypt)** for the sponsored supply of concrete mixes and concrete patches. Special thanks are extended to the technicians at the Structural Laboratory of Ain Shams University for their help during the experimental program.

I would like to thank my friend Mahmoud Mounir for his steadfast encouragement and advice.

Finally, special appreciation goes to my wife, her substantial encouragement and support helped me to finalize my research. Hence, to her this thesis is dedicated.

To my parents, whom, I owe too much. To my wife whom encouraged me so much.

التخصص : الهندسة الإنشائية
القســـــم :الهندسة المدنية
الدرجـــة : الماجستير

الكود :
تاريخ الميلاد : 18-1-1978
البكالوريوس : **جامعة عين شمس**- 2000
تاريخ منح الدرجة : 20-3-2013

محمد عمر الصاوى محمد

هيئة الإشراف :
أ.د. عمرو على عبد الرحمن
أ.د. طارق كمال حسان

لجنة الفحص و الحكم:
أ.د. عادل العطار
أ.د. على شريف عبد الفياض

دراسه خواص التماسك في الكمرات المصنعه من الخرسانه ذاتيه الدمك

تم التركيز من خلال هذا البحث علي دراسه تأثير كل من مقاومه الضغط للخرسانه و المسافه بين الاسياخ والغطاء الخرساني عل مقاومة التماسك بين الخرسانه ذاتيه الدمك واسياخ الحديد للكمرات الخرسانيه.
تم تقييم سلوك الكمرات المصنعه من الخرسانه ذاتيه الدمك عمليا وتحليليا. يقدم البحث اعتبارات تصميميه واضحه لاستخدام الخرسانه ذاتيه الدمك في االكمرات الخرسانيه المسلحه.
تم صب عدد 8 كمرات مستطيله المقطع واختبارها تحت ظروف تحميل استاتيكيه وتم اختبار خرسانه ذات قيم مختلفه لمقاومه الضغط تتروح بين (30 ميجا باسكال)الي (60 ميجاباسكال). كما تم دراسة قيم مختلفه للغطاء الخرساني للكمرات. وامتد البحث ليشمل دراسه تأثير عدد الوصلات والمسافه بين الاسياخ علي مقاومة الانزلاق للأسياخ داخل الخرسانيه ذاتية الدمك.
الاستقصاء التحليلي يلقي بالضوء على تقييم دقيق للنماذج المتعدده التي تمثل العلاقه بين اجهادات الرابطه والانزلاق لحديد التسليح المرتبط بالخرسانه و امكانية استخدامها في الخرسانه ذاتيه الدمك. و تم تطويرالنموذج لتحديد طول الرباط المطلوب لتحقيق اجهاد الخضوع لاسياخ حديد التسليح المستخدمه مع الخرسانه ذاتيه الدمك.
كما تم عمل دراسة تحليلية بإستخدام طريقة العناصر الغير محددة عن طريق إستخدام برنامج (ATENA) لتمثيل بعض الكمرات في هذا البحث و بحث سابق تم إجرائة بجامعة عين شمس. و ذلك لتأكيد ما تم التوصل إليه من نتائج معملية. و قد أظهرت النتائج إثبات أن مقاومة التماسك للخرسانة ذاتية الدمك أقل بنسبة 24% من الخرسانة التقليدية. كما تم التوصل الى معيار للإنهيار مقاومة التماسك للخرسانة تم تعميمه على جميع الكمرات موضوع هذه الدراسة.

BOND CHARACTERISTICS OF SELF CONSOLIDATING REINFORCED CONCRETE BEAMS

The application of Self Consolidating Concrete, SCC, effectively resolves the difficulties of concreting in situations with complicated formwork and intricate reinforcements. Although, bond between SCC and reinforcing steel bars is an essential requirement for design of reinforced concrete structures, little research is available up to date on this topic. This study is a continuation of a recent study conducted to evaluate the effect of the bar diameter, splice length and the confinement level provided by the transverse reinforcement. The current study aims at widening the available knowledge on the bond characteristics of SCC members by including other parameters that have not been studied previously. The current research focus on studying the influence of the concrete compressive strength, bar spacing and concrete cover on the bond characteristics of SCC beams. Eight reinforced concrete beams were constructed using different concrete strengths varies between 30 to 60 MPa, and tested under four point bending. The behavior of the tested specimens has been evaluated and characterized both experimentally and analytically. A finite element study has been conducted using ATENA software to ensure the experimental results, this study adopt that bond strength of SCC is less than the conventional concrete by 24%. Failure criteria due to bond has been established and applied on all the selected beams.

Abstract

The application of Self Consolidating Concrete, SCC, effectively resolves the difficulties of concreting in situations with complicated formwork and intricate reinforcements. Although, bond between SCC and reinforcing steel bars is an essential requirement for design of reinforced concrete structures, little research is available up to date on this topic. This study is a continuation of a recent study conducted to evaluate the effect of the bar diameter, splice length and the confinement level provided by the transverse reinforcement. The current study aims at widening the available knowledge on the bond characteristics of SCC members by including other parameters that have not been studied previously. The current research focus on studying the influence of the concrete compressive strength, bar spacing and concrete cover on the bond characteristics of SCC beams. The behavior of the tested specimens has been evaluated and characterized both experimentally and analytically. A finite element study conducted using ATENA software to ensure the experimental results, this study adopt that bond strength of SCC is less than the conventional concrete by 24%. Failure criteria due to bond has been established and applied on all the selected beams.

Table of Contents

Acknowledgement vi
Abstract ix
Table of Contents x
List of Figures xvii
List of Tables xvii

Chapter 1: Introduction 1
1.1 General 1
1.2 Research Objective 2
1.3 Scope 2

Chapter 2: Literature Review 5
2.1 Introduction 5
2.2 Self- consolidating concrete (SCC) 5
2.3 Fresh Concrete Properties 9
2.3.1 Slump-flow 9
2.3.2 Viscosity 11
2.3.3 Passing ability 11
2.3.4 Segregation resistance 13
2.4 Engineering properties 14
2.4.1 General 14
2.4.2 Compressive strength 15
2.4.3 Tensile strength 16
2.4.4 Static modulus of elasticity 16
2.4.5 Creep 17
2.4.6 Shrinkage 18
2.4.7 Coefficient of thermal expansion 20
2.4.8 Bond to reinforcement, pre-stressing and wires 20
2.4.9 Shear force capacity across pour planes 21
2.4.10 Fire resistance 22
2.4.11 Durability 23
2.5 SCC Fresh Property Evaluation and Quality Control 24
2.5.1 Slump-flow and T500 Test 24
2.5.2 V-funnel Test 30
2.5.3 L-box test 34
2.5.4 Sieve Segregation Resistance Test 39

2.6 Bond Behavior 42
2.6.1 Bond Forces 47
2.6.2 Factors Affecting Bond Strength: 52
2.6.2.1 Effect of Concrete Cover and Bar Spacing 53
2.6.2.2 Effect of Concrete Compressive Strength 55
2.6.3 Bond Strength Descriptive Equations 59
2.6.3.1 Orangun, Jirsa and Breen (1975, 1977) 59
2.6.3.2 Darwin et al. (1992) 60
2.6.3.3 Zuo and Darwin (1998, 2000) 62
2.6.3.4 Esfahani and Rangan 63
2.6.3.5 ACI Committee 408 64
2.6.4 Splice Length Design Equations 65
2.6.4.1 ACI 318-02 65
2.6.4.2 CSA A23.3-94 66
2.6.5 Modeling for bond between reinforcing bars and concrete: 68
2.6.5.1. Bering angle model: 68
2.7 Bond between steel reinforcing bars and SCC 71
2.8 Bond characteristics of conventional concrete beams reinforced with high-strength steel reinforcement. (Hassan et al 2012) 75

Chapter 3: Design and Fabrication of Test Specimens 77
3.1 Introduction 77
3.2 Specimens Details and Identification 77
3.2.1 Specimens Details 77
3.2.2 Specimen Identification 79
3.3 Self-Consolidating Concrete (SCC) 81
3.4 Fresh Concrete Property Testing 83
3.4.1 Slump flow test: 83
3.4.2 V-funnel Test: 85
3.4.3 L-box test: 86
3.5 Hardened Concrete Property Testing: 88
3.6 Reinforcing Steel Bars: 89
3.7 Specimen Fabrication: 89
3.7.1 Operations prior to casting: 89
3.7.1.1 Form work: 89
3.7.1.2 Reinforcement Fabrication: 90
3.7.2 Casting Operation 92
3.7.3 Instrumentation Installation 94
3.8. Testing Procedure 97

3.8.1 Test Setup 97

Chapter 4: Experimental Results 99
4.1 Introduction 99
4.2 Experimental Measurements 99
4.3 General behavior and mode of failure 101
4.4 Influence of Concrete Compressive Strength 111
4.5 Influence of Number of Spliced Bars 113
4.6 Influence of Concrete Cover 114

Chapter 5: Analytical Modeling 115
5.1 Introduction 115
5.2 Comparison of Bond Descriptive Equations 115
5.3 Analysis of Test Results 121
5.4 Comparison with Various Codes 125

Chapter 6: Finite Element Modeling 131
6.1 Introduction 131
6.2 Introduction to FE Modeling 131
6.3 Finite Element Method 131
6.4 Finite Element Modeling 132
6.5 Material Models 133
6.5.1 Modeling of Concrete 133
6.5.2 Modeling of Reinforcement 134
6.6 Stress-Strain Relationship for Concrete 135
6.7 Stress- Strain Law for Reinforcement 136
6.8 FE Modeling Of Reinforced Concrete Beams in ATENA 137
6.9 Methods for Non-Linear Solution 139
6.10 Proposed Criteria Due to Bond Failure 140
6.11 Verification of the FE bond model 141
6.12 Application of FE model on SCC 149
6.12.1 Modeling of Beam B7 149
6.12.2 Modeling of Beam Group I; Beams (B1, B2 & B3) 153

Chapter 7 157
7.1 Summary 157
7.2 Conclusions 158
7.3 Recommendations 160

References 161

List of Figures

Figure 2-1 Baseplate for slump flow test 27
Figure 2-2 V funnel 32
Figure 2-3 General assembly of L-box 36
Figure 2-4 Dimensions and typical design of L-box 36
Figure 2-5 Bond force transfer mechanisms 44
Figure 2-6 Cracking and damage mechanisms in bond 46
Figure 2-7 Variation in bar force due to changes in moment in a beam .. 47
Figure 2-8 Variation of steel and bond forces in a reinforced concrete member subjected to pure bending 49
Figure 2-9 Schematic Typical splitting failure patterns for varying bottom and side 53
Figure 2-10 Variation of test-prediction ratio versus compressive strength for developed/spliced bars not confined by transverse reinforcement. 57
Figure 2-11 Variation of test-prediction Best-fit lines for test-prediction ratios versus compressive strength for developed/spliced bars confined by transverse reinforcement. 58
Figure 2-12 Flattened rib face angle by concrete crouching 69
Figure 2-13 Schematic analysis of bond strength by bearing angle model (different confinement) 70
Figure 2-14 Schematic analysis of bond strength by bearing angle model (different rib height) 70
Figure 3-1 Beams cross section detail 78
Figure 3-2 Test Specimens 79
Figure 3-3 Overall view for concrete plant indicates mix for concrete materials 82
Figure 3-4 Overall view for concrete plant indicates dispatch for SCC . 82
Figure 3-5 Overall view for concrete plant indicates transfer for SCC patch to casting location 83
Figure 3-6 Test sample 84
Figure 3-7 Temperature measurement 84
Figure 3-8 Slump spread test apparatus 84
Figure 3-9 Fill the cone with SCC 84
Figure 3-10 Raise the cone and spread of SCC 84
Figure 3-11 Measurement of spread 84
Figure 3-12 V-funnel Test apparatus 85

Figure 3-13 Fill funnel with SCC 85
Figure 3-14 Transfer for SCC from the funnel to the container 86
Figure 3-15 L-box Test apparatus 87
Figure 3-16 SCC flow through 87
Figure 3-17 Measurement of concrete height 87
Figure 3-18 SCC samples for cylindrical compressive strength test 88
Figure 3-19 Preparation of forms 90
Figure 3-20 coat forms with lubricant film 90
Figure 3-21 Bottom reinforcement splice 91
Figure 3-22 Reinforcement cadges for specimens 92
Figure 3-23 Preparation for SCC pouring 93
Figure 3-24 SCC pouring 93
Figure 3-25 Flow for SCC inside forms 93
Figure 3-26 Electrical strain gages fixed on rebar 95
Figure 3-27 LVDTs fixed under test specimens (front view) 95
Figure 3-28 LVDTs fixed under test specimens (upward view) 96
Figure 3-29 Schematic for test setup and the applied Instrumentation 97
Figure 3-30 Actual test setup 98
Figure 4-1 Typical splitting failure at the splice zone (Current research) 102
Figure 4-2 Typical splitting failure at the splice zone (Previous research) 102
Figure 4-3 Failure mode of B1 103
Figure 4-4 Crack pattern of B1 (Front view) 103
Figure 4-5 Crack pattern of B1 (Over head view) 103
Figure 4-6 Failure mode of B2 104
Figure 4-7 Crack pattern of B2 (Front view) 104
Figure 4-8 Crack pattern of B2 (Over head view) 104
Figure 4-9 Failure mode of B3 105
Figure 4-10 Crack pattern of B3 (Front view) 105
Figure 4-11 Crack pattern of B3 (Over head view) 105
Figure 4-12 Failure mode of B4 106
Figure 4-13 Crack pattern of B4 (Front view) 106
Figure 4-14 Crack pattern of B4 (Over head view) 106
Figure 4-15 Failure mode of B5 107
Figure 4-16 Crack pattern of B5 (Front view) 107