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BEHAVIOR OF SELF– COMPACTED CONCRETE DEEP BEAMS WITH REINFORCED COMPRESSIVE STRUTS

A Thesis Submitted to Council of College of Engineering, University of Diyala in Partial Fulfillment of the Requirements for the Degree of Master of Science in Civil Engineering

By

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DEDICATION

First to our teacher to whom rise his saying in the worlds

(Mohammed) and to the people of house, (Ahl Al-bayt)

To the person who will make the women a sacred entity freestanding,

(Imam Al-Mehdi)

To the apple of my eyes and the scent of my life, my dear Mom.

To whom I seek as a shelter after my God (Allah), my dear Dad.

To those who were always standing to my side,

To my brothers and my sisters, specially brother "Mohammed".

I offer this humble efforts to remain proud of it.

Sarah Farhan Jebur

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Behavior of Self– Compacted Concrete Deep Beams with Reinforced Compressive Struts

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ABSTRACT

The main aim of this research was to study the behavior of self compacted concrete deep beams when reinforcing their struts based on the STM of ACI 318M-14. The experimental program contained casting and testing nine specimens divided into three groups. The difference between the three groups was the type of loading; 2-concentrated forces, 1-concentrated force and uniformly distributed load. Every group contained three specimens. The first specimens of each group were the conventional reference deep beams. The second specimens of each group were the specimens in which only the struts and ties paths were reinforced in addition to removing concrete shoulders (in order to save cost, reduce weight and provide a front side area for services). The third specimens of each group were the RC frames that their shapes were defined by the STM of ACI 318M-14. The struts and ties of these frames were reinforced as compression members and as tension members, respectively.

The effect of reinforcing struts and ties, response of load-deflection, cracking load, deflection at first crack, cracks characteristics (spreading, width, number and type of cracks), strain in steel bars, strain in the surface of concrete, the contribution of reinforcement to the strength of the struts and ties in addition to failure conditions were studied.

The experimental results exhibited that the first specimens (references) of each group showed superiority in terms of ultimate capacity about 20% in comparison with the theoretical design loads of STM, ACI 318M-14. The second specimens of each group (where only the paths of struts and ties were reinforced) in addition to

the third specimens of each group (RC struts and ties frames) exhibited acceptable differences with the theoretical design loads of STM, ACI 318M-14. Accordingly, these frames were good alternatives for the reference beams because of cost saving, reducing weight and providing a front side area which amounted to 4-27%, 41-51% and 46-56%, respectively.

Measuring strain assisted in investigating the contribution of reinforcement to the strength of the struts. For example, in the case of the frames, the contribution in inclined struts was 29%, 53% and 30% in cases of 2-concentrated forces, 1-concentrated force and uniformly distributed load, respectively. These experimental contribution ratios were close to equations of (ACI 318M-14). Measuring strain also assisted in more clarifying the failure type that took place in the specimens.

For all specimens, measuring the width of the first cracks assisted in observing that the first flexural cracks did not exceed limits of crack width, so they were not critical. While the first shear cracks exceeded the limits and they were critical.

In addition to the experimental work, a numerical analysis of these nine specimens using the finite element program ANSYS 13 has been conducted. The numerical results of this analysis showed good agreement with the experimental ones. Besides, the numerical effects of concrete compressive strength (f'_c) and reinforcement yield stress (f_y) on the ultimate capacity and the midspan deflection of the proposed reinforced SCC specimens were investigated. It was found that the increase in concrete compressive strength (f'_c) about 33.3% led to increase both the ultimate capacity and the midspan deflection about 7-13% and 20-70%, respectively for the specimens in which only the struts and ties were reinforced. While for the RC frames, the increase in both the ultimate capacity and the midspan deflection was about 5-11% and 15-41%, respectively. It was also found that the increase in reinforcement yield stress (f_y) about 40% led to increase the ultimate capacity and decrease the midspan deflection about 22-38% and 8-15%, respectively for the specimens in which only the struts and ties were reinforced. While for the RC frames, the increase in the ultimate capacity and the decrease in midspan deflection were about 26-40% and 19-28%, respectively.

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a	Shear span measured from center of load to center of support, mm
d	Effective depth of beam, distance from extreme compression fiber to centroid of longitudinal tension reinforcement, mm
h	Total depth of deep beam, mm
P_u	Ultimate load of deep beam, kN
P_{STM}	Theoretical load according to Appendix A, ACI 318M-14 Strut and Tie method, kN
V_n	Nominal shear strength, kN
W	Uniformly distributed load, kN/m
P_{Num}	Numerical failure load, kN
$P_{cr-flex}$	First flexural cracking load, kN
$P_{cr-diag}$	First diagonal cracking load, kN
P_{vis}	Visual shear cracking load, kN
P_{est}	Estimated shear cracking load from strain, kN
$\Delta_{cr-flex}$	Displacement corresponding to the 1st flexural crack load, mm
$\Delta_{cr-diag}$	Displacement corresponding to the 1st diagonal crack load, mm
Δ_u	Displacement corresponding to the ultimate of deep beam, mm
Δ_{Num}	Numerical displacement at failure, mm
b	Width of beam, mm
f'_c	150mm*300mm Cylinder compressive strength of concrete, MPa
f_r	Modulus of rapture, MPa
f_{ct}	Indirect tensile strength (splitting tensile strength), MPa
f_y	Yield stress (MPa)
j_d	Moment arm, mm
L_n	Clear span length of deep beam, mm
L	Overall length of deep beam, mm
l_b	Length of load bearing block, mm
l_s	Length of support bearing block, mm
ε_{yield}	Strain at yield
P_s	Nominal tensile strength, MPa
P_c	Nominal compressive strength,MPa
E_c	Modulus of elasticity of concrete, MPa
E_s	Modulus of elasticity of steel reinforcement, MPa
ϕ	Diameter of bar, mm
ρ_v	Vertical web reinforcement ratio
ρ	Flexural reinforcement ratio
A_s	Area of main longitudinal tension reinforcement, mm^2
A_{sv}	Area of vertical web shear reinforcement, mm^2
A_{sh}	Area of horizontal web shear reinforcement, mm^2
A_{sb}	Area of reinforcement bars, mm^2
A_g	Area of column cross section, mm^2
f_{yv}	Yield stress of vertical web reinforcement, MPa
f_{yh}	Yield stress of horizontal web reinforcement, MPa
S_v	Spacing of vertical shear reinforcement, mm

S_{vh}	Spacing of horizontal shear reinforcement, mm
f_{ce}	Effective compressive strength of the concrete in a strut or a nodal zone, MPa
w_s	Width of horizontal strut, mm
w_t	Width of anchor tie, mm
w_{sb}	width of strut at support nodal zone , mm
w_{st}	width of strut at load nodal zone, mm
w_{eff}	Effective width of strut, mm
θ	Angle of inclination of the diagonal compressive stress and the failure plane with the beam longitudinal axis in right side, degree
α_1, α_2	Angle of inclination of reinforcement to the axis of the beam, degree
β_n	Nodal zone coefficient
β_s	Factor to account for the effect of cracking and confining reinforcement on the effective compressive strength of the concrete in a strut

ACI	American Concrete Institute
ASCE	Japan Society of Civil Engineers
SCC	Self Compacted Concrete
EFNARC	European Federation of National Trade Associations Representing Concrete
STM	Strut and Tie Model
CCT	Compression- Compression- Tension
a/d	Shear span to effective Depth ratio
ANSYS	Analysis System
FE	Finite Element
RC	Reinforced Concrete
NC	Normal strength Concrete
a/h	Shear span to Overall depth ratio
CSA	Canadian Standard Association
AASHTO LRFD	American Association of State Highway and Transportation Officials
L_n/h	Clear span to Overall depth ratio
ASTM	American Society for Testing and Materials
I.Q.S	Iraqi Standard Specification
HPSCA	High Performance Superplasticizer Concrete Admixture
H_2/H_1	The blocking ratio
AISC-LRFD	American Institute of steel construction load and resistance design specification
ASTM	American Society for Testing and Materials
c/c	Center to center clear span, mm
SP	Superplasticizer

CHAPTER ONE
INTRODUCTION

1.1 General

The term deep beams applies to any beam which has a ratio of depth to span sufficient to make the shear stresses distribution to be non-parabolic and to cause non-linearity in the elastic flexural stresses through the depth of beam (Varghese and Krishnamoorthy, 1966). Another common characteristic of these special members is that, in addition to main flexural reinforcement, they have orthogonal reinforcement distributed throughout the member (ACI-ASCE Task Committee 426, 1985). The deep beams strength is generally governed by shear more than flexure. Then, because of the special ability for deep beams to redistribute internal forces before collapse and to develop mechanisms of force flow, the shear strength of deep beam is significantly greater than that expected using expressions developed for slender beams (Subedi, et al., 1986).

The American Concrete Institute Code (ACI), (ACI Committee 318M, 2014) describes deep beam as:

Member subjected to loads on one surface and supported on the opposite surface so that the compression struts can grow between the points of load and the supports. Deep beam has one or the other:

1) Clear spans L_n, less than or equal to 4 times the whole member depth; or
2) Concentrated load zones within double the member depth from the support face.

For deep beams that loaded uniformly, the shear critical section should be taken into consideration at a distance from face of support about ($0.15 L_n \leq d$) and of ($0.5 a \leq d$) for concentrated loaded deep beams, where (a) is the shear span, or distance from concentrated load to the support center and (d) is the distance from extreme compression fiber to the centroid of the tension steel bars (Merritt and Ricketts, 2000).

The reinforced concrete (RC) deep beams are very essential structural members in various types of concrete structures. They are distinguished as being generally deep and short, having a small thickness relative to their span or depth. Typical uses of deep beams comprise foundation pile caps, transfer girders, tanks, foundation walls, shear walls, folded plates of roof structures and offshore structures. Frequently receiving many small loads in their own plane and transporting them to a small number of reaction points (Ashour and Yang, 2008).

1.2 Self- Compacted Concrete

Since the deep beams have congested reinforcement, the problem of filling spaces between steel bars is serious. Therefore, self-compacted concrete (SCC) is the suitable way to be used for casting those deep members. SCC is that kind of concrete that can flow freely through places by its own weight and fills restricted areas between congested steel bars without vibration (Kaszynska, 2004). This special kind of concrete is different from the traditional concrete because it has a lesser viscosity and, therefore, more rate of flow when pushed; it as well has no blocking tendency, no bleeding and suitable flowability. It has almost a horizontal concrete level after placing (Ozawa, et al., 1989).

SCC has several further names such as Self-leveling concrete, High-workability concrete, (Yang, 2004) or flowing concrete (Bui, et al., 2002).

EFNARC (2002) defined SCC as concrete that has the capability to flow under its own weight and wholly fill the moulds, even in the existence of congested steel bars, with no necessity to vibration, together as keeping homogeneity.

ACI Committee 237R-07, describes SCC as greatly flow capable, no segregation concrete that can spread and fill the moulds, and surround the steel bars without any vibration.

SCC can be cast in conditions where it is impossible or difficult to use fresh concrete vibration, for example, cast in site pile foundations, underwater concreting, walls or columns that have crowded steel bars and machine bases (Patel, et al., 2011).

The advantages of SCC that should be taken into consideration for each producer may comprise as follows (Koehler, 2007):-

1-Developing the capability of concrete to flow into dense reinforcement bars and difficult forms.

2- Decreasing the need to repair defects such as bug holes.

3- Decreasing production costs due to decreasing equipment buying and decreasing labor costs in addition to maintenance costs.

4- Due to fewer construction tasks, therefore, increasing construction speed can be added here.

5- Quick unloading of ready mixed concrete vans.

6- Due to elimination of vibrators, therefore, improves working conditions with fewer accidents.

7- Improving the strength and durability of the hardened concrete in some cases.

8- Decreasing noise produced by vibrators.

The disadvantages of SCC may contain:-

1- Increasing material costs, specifically for cementations materials and admixtures.

2- Due to possibly higher formwork pressures, therefore, increases the cost of formwork.

3- Increasing technical experience needed to improve the mixes.

4- Increased variability in properties, especially workability.

5- Increasing quality control requests.

6-Decreasing hardened concrete properties- possibly comprising dimensional stability and Young Modulus- cause of low coarse aggregate contents or high paste volumes.

7- In some cases, delaying the setting time.

1.3 Modes of Failure of RC Deep Beams

Several factors affect the behavior of deep beams such as clear span/depth ratio (L_n/d), shear span/depth ratio (a/d), the position of the load, type of loading, tensile steel percentage, web steel bars, the support zone width, main steel bars anchorage, concrete compressive strength and additives like fibers, waste plastic …. etc.., (Subedi, et al., 1986).

Deep beams failure can be summarized as follows: (ACI-ASCE Task Committee 426, 1973):

1. **Flexural failure:** when the beam has a large a/h ratio with low tensile steel percentage, it will fail by steel reinforcement yielding at a maximum moment region as shown in Figure (1-1).

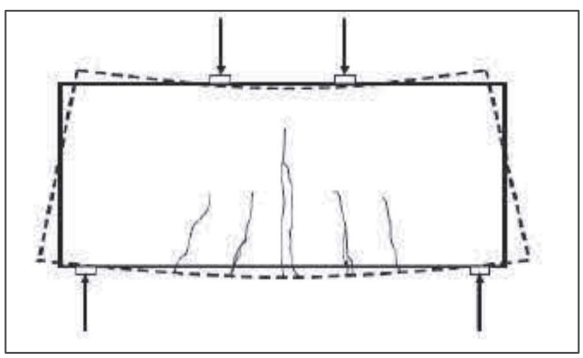

Figure (1-1): Flexural failure of deep beam

2. **Flexural-shear failure:** when there is an enough amount of tension reinforcement and the improvement of the inclined diagonal cracks are headed by flexural cracks at the maximum moment zone, the main cracks will produce the failure. Cracks that cause the failure will spread upwards

beginning from the zone of support to the zone of load as shown in Figure (1-2).

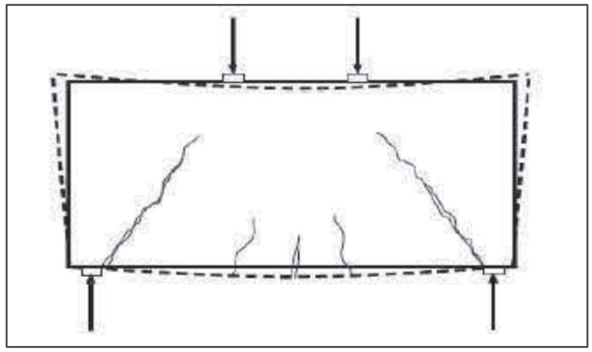

Figure (1-2): Flexural-shear failure of deep beam

3. **Diagonal splitting failure:** when the final diagonal crack extends between the support and the load and it propagates outwards from the midspan, diagonal splitting failure will occur as shown in Figure (1-3).

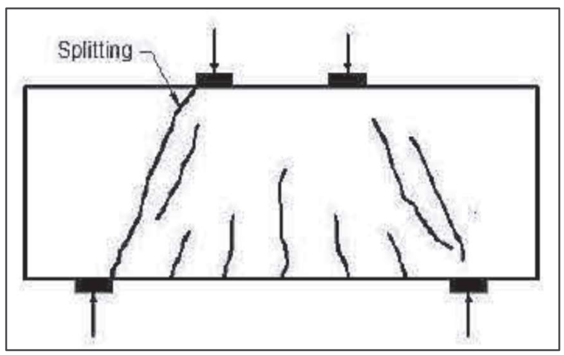

Figure (1-3): Diagonal splitting failure of deep beam
(Kong, at el., 1970)

4. **Diagonal compression failure:** First, an inclined crack develops about the line joining the support and the load. After an additional load increase, another parallel inclined crack develops nearer to the supporting point than the first inclined crack and develops upwards as increasing of the load takes place. The final failure is due to the demolition of the part of concrete between the first and second cracks that makes like a strut between the support and the load points as shown in Figure (1-4).

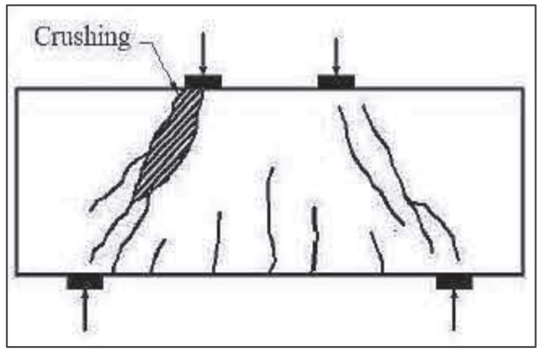

Figure (1-4): Diagonal compression failure of deep beam (Kong, at el., 1970)

5. **Bearing failure:** due to the increase of high stresses in the loaded areas or above the supports regions, this failure occurs; see crack No.1 in Figure (1-5).
6. **Bond failure (Anchorage failure):** it takes place about the beam ends, where high flexural bond stresses can combine with high local bond stresses as shown by crack No.2 in Figure (1-5). To avoid bond failures, the longitudinal reinforcement may be anchored by a plate or through the embedment of straight bars, headed bars, or hooked bars ACI 318M-14 (R23.2.6). A standard hook can be used, as defined by ACI 318M-14 (25.3.1), contains a bend of 90-degree with 12 times the diameter of the bar behind the bend as extension. The hook must be positioned at that point where the bars are fully developed. Strut and Tie Model (STM) states that the longitudinal tension reinforcement of the tie could be fully developed at compression-compression-tension (CCT) vertical face at every support node. Bearing and anchorage failure in deep beam is shown in Figure (1-5).

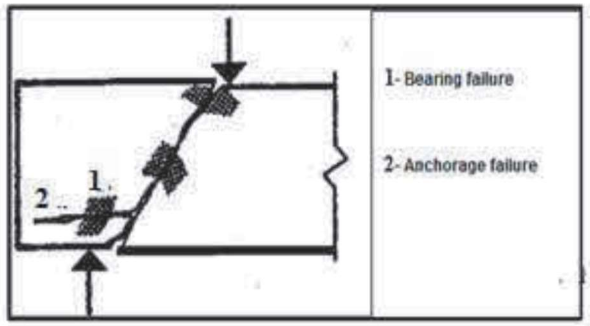

Figure (1-5): Bearing and Anchorage failures in deep beam

1.4 Crack Types in RC Deep Beams

Figure (1-6) shows types of cracks in RC deep beam. Flexural cracks propagates from the deep beam soffit. In addition, there are two types of shear cracks that are known in RC deep beams; web-shear cracks and flexure-shear cracks (MacGregor and Wight, 2005). Flexure-shear cracks appear after or at the same time of the flexural crack formation. They develop from the end of the flexural crack towards the load origin. Web-shear cracks appear separately of flexural cracking. They appear when the principal stress of tension in the member web becomes more than the concrete tensile strength. Web-shear cracks in deep beams are indicated as splitting or bursting cracks. Generally, web-shear cracks are formed by transverse tensile stresses that take place due to the distribution of compressive stresses that exist in the bottle-shaped struts. It is apparent that the spreading of compressive stresses in deep beams contributes to the width of flexure-shear cracks as well.

It is worth mentioning that the steel stress, concrete cover, and bar spacing are major variables affecting the flexural crack width (Nawy, 1991). In addition, several primary variables affecting the diagonal crack width are transverse reinforcement, (a/d) ratio, longitudinal reinforcement, concrete cover (Birrcher, et al., 2009).

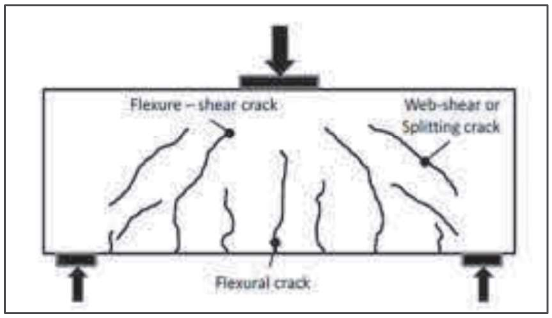

Figure (1-6): Types of cracks in reinforced concrete deep beam (MacGregor and Wight, 2005)

1.5 Using Strut and Tie Model for Deep Beams

The Strut-and-Tie Model (STM) shown in Figure (1-7), is especially suitable in the strength estimate of discontinuity regions. The flow of forces can be easily imagined by classifying the discontinuity regions with compressive struts representing the flow of concentrated compressive stresses in the concrete. While the tension ties are representing the reinforcing steel (Hwang and Lee, 2002).

The use of STM involves getting far from the traditional approach of design. While engineers must stand by a basic set of guidelines in choosing the configuration of STM, they are allowed to choose any model considered suitable for a particular problem. The actual choice of STM is proposed to represent the path followed by internal forces inside the structural element. The flexibility afforded by this method allows the development of multiple solutions for the same problem. For the reason that numerous aspects affect the reinforcement quantity and distribution in deep beams, understanding their behavior is necessary to the solution of strut and tie models that lead to rational designs (Matamoros and Wong, 2003).

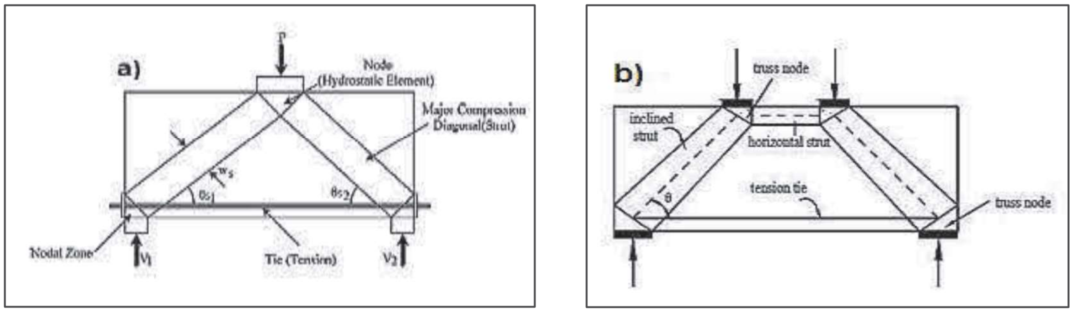

Figure (1-7): STM in deep beams (a) (Brown, et al., 2006), (b) (El-Sayed, 2014)

1.6 Objectives of the Present Work

The main objectives of this study are investigating STM performance when reinforcing the compressive struts by steel bars. This could help to remove the zones that STM does not care about (the zones where the struts and ties do not pass through). In other words, the work takes into considerations the paths of struts and reinforcing them according to ACI 318M-14**.** Therefore, this investigation is divided into two phases:

a. Experimental Work Phase: The experimental work is carried out to investigate the behavior of SCC deep beams when reinforcing their compressive struts. This was conducted under three types of loading:

- Single concentrated load,
- Two concentrated loads, and
- Uniformly distributed load.

b. Numerical Analysis Phase: The numerical analyses are carried out using (ANSYS 13) FE program to validate the experimental work, then to study the effect of the compressive strength of concrete (f'_c) and yield stress of steel reinforcement (f_y) on the ultimate capacity, crack pattern and load-midspan deflection response for the tested SCC specimens.

1.7 Thesis Layout

The thesis is offered in six chapters:

- **Chapter One** presents a general introduction about RC deep beams, SCC, STM, in addition to the objectives of the study.
- **Chapter Two** presents a review of previous researches with experimental studies carried out in SCC deep beams and STM.
- **Chapter Three** deals with the used construction materials properties in addition to the experimental work.
- **Chapter Four** deals with presenting test results of the laboratory specimens, discussing and evaluating the experimental results of this study.
- **Chapter Five** presents the modeling of the experimental specimens by finite element as well as conducting a parametric study for the parameters that affect the ultimate capacity and the deflection.
- **Chapter Six** provides the conclusions drawn from this study, recommendations and suggestions for further studies.