Ministry of Higher Education
and Scientific Research
University of Diyala
College of Engineering

REINFORCING STRUTS AND TIES IN CONCRETE RING DEEP BEAMS – BEHAVIOUR AND STRENGTH

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
Wisam Hazim Khaleel
(B.Sc. in Civil Engineering, 2009)

Supervised by
Prof. Khattab Saleem Abdul-Razzaq, (Ph. D.)

August, 2021 **IRAQ** **Muharram, 1443**

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

﴿يَرْفَعِ اللَّهُ الَّذِينَ آمَنُوا مِنْكُمْ وَالَّذِينَ أُوتُوا الْعِلْمَ دَرَجَاتٍ
وَاللَّهُ بِمَا تَعْمَلُونَ خَبِيرٌ﴾

صدق الله العظيم

المجادلة (١١)

Certification

I certify that the thesis entitled **"Reinforcing Struts and Ties in Concrete Ring Deep Beams - Behaviour and Strength"** was prepared by **"Wisam Hazim Khaleel"** under my supervision at the Department of Civil Engineering-College of Engineering-Diyala University in a partial fulfillment of the Requirements for the Degree of **Master of Science in Civil Engineering**.

Signature:
Supervisor: Prof. Dr. Khattab Saleem Abdul-Razzaq
Date: / /2021

In view of the available recommendation, I forward this thesis for debate by the examining committee.

Signature:
Name: Prof. Dr. Khattab Saleem Abdul-Razzaq
Head of the Department of Civil Engineering
Date: / /2021

COMMITTEE DECISION

We certify that we have read the thesis entitled " **Reinforcing Struts and Ties in Concrete Ring Deep Beams - Behaviour and Strength** " and we have examined the student **(Wisam Hazim Khaleel)** in its content and what is related with it, and in our opinion, it is adequate as a thesis for the Degree of Master of Science in Civil Engineering.

Examination Committee **Signature**

1- Prof. Dr. Khattab Saleem Abdul-Razzaq (Supervisor)..................

2- Prof. Dr. Haider K. Ammash (Chairman) ....

3- Assist. Prof. Dr. Ahmed A. Mansor (Member) ....

4- Lec. Dr. Assal T. Hussein (Member)...

Prof. Dr. Wissam D. Salman ....(Head of Department)

The thesis was ratified at the Council of College of Engineering / University of Diyala.

Signature ....
Name: Prof. Dr. Anees A. Khadom
Dean of College of Engineering / University of Diyala
Date: / / 2021

DEDICATION

All praise to Allah, today I leave the days' tiredness and the errand summing up between the covers of this humble work…

To the utmost knowledge lighthouse, to our greatest and most honored Prophet Mohamed (Peace Be Upon Him) …

To whom he strives to bless comfort and welfare and never stints what he owns to push me in the success way, who taught me to promote life stairs wisely and patiently, to my dearest father…

To the spring that never stops giving, to my mother who weaves my happiness with strings from her merciful heart...

To who always helps and supports me... my brothers and sister…

Wisam Hazim Khaleel

2021

ACKNOWLEDGEMENTS

In the name of Allah, the most gracious, the most merciful, before anything, I thank ***ALLAH*** *who enabled me to achieve this research.*

First, I wish to express my sincere gratitude and appreciation to the supervisor; ***Prof. Khattab S. Abdul-Razzaq (Ph. D.)*** *for his supervisions, precious advices, technical guidance, continuous encouragements, and remarkable patience in reviewing my thesis and stop me pause forearm to a person's, I'm really indebted to him.*

My thanks go as well to ***all friends*** *who have gave advice and did not complain of frequent questions especially* ***Asala A. Dawood, Abdullah A. Talal*** *and* ***Azaher S. Ibrahim.***

Great thanks to the staff of ***Structural Engineering Laboratory*** *in addition to my teachers in the* ***Department of Civil Engineering*** *for their cooperation and help.*

I would like to express my thanks, appreciation and gratitude to ***my family*** *for their support and patience that helped me in achieving this study, which is the fruit of my entire family.*

Wisam Hazim Khaleel

2021

Reinforcing Struts and Ties in Concrete Ring Deep Beams - Behaviour and Strength

ABSTRACT

The current research work aims at studying the behavior and strength of reinforced concrete ring deep beams when replacing the conventional reinforcement by reinforcing the struts and ties only. The paths of the compressive struts and tensile ties are defined through adopting the STM of Chapter 23, ACI 318M-19. The experimental program contained casting and testing eight specimens divided into three groups, A, B and C. Group A and B contained the specimens that had a ring diameter of 1000 mm, a height of 400 mm, a width of 120 mm, strut-tie angle of 30°, and they rest on 3 supports. While group C contained the specimens that had a ring diameter of 1000 mm, a height of 400 mm, a width of 100 mm, strut-tie angle of 38°, and they rest on 4 supports. More specifically, Group A contained three specimens in which the first one was the conventionally reinforced control ring deep beam.

The second specimen was solid ring deep beam in which only struts and ties are reinforced, while the third specimen was proposed frame that took its geometry and dimensions from the stress paths of STM, ACI 318M-19. The first specimen in Group B was a solid control ring deep beam in which only ties were reinforced, while the second specimen was the proposed frame in which only ties were reinforced. Finally, group C contained three 4-supported specimens that had a width of 100 mm. The first one was the solid conventionally reinforced control specimen. The second specimen was the proposed frame in which only struts and ties are reinforced, while the third one was the proposed frame in which only ties are reinforced. All specimens were tested using increasing monotonic static single midspan concentrated force.

The experimental ultimate capacity load, load-deflection response, load-lateral displacement response, first crack load, deflection at first crack, cracks characteristics such as type, width and propagation, average strain values in concrete surface, strain in steel bars, deflection at ultimate load capacity in addition to failure modes and failure loads are recorded and studied. It was concluded that the behavior of both the reference and proposed specimens is approximately similar except at the final loading stages. The proposed specimens did not exceed the reference specimens in terms of experimental ultimate capacity, but in all cases, they exceeded the theoretical STM, ACI 318M-19 design load. Wherefore, the specimens in groups A, B, and C showed a decline in the experimental ultimate capacity compared with their reference specimens by about 10.7-31%, 13.4% and 12.9-15.6%, respectively, but in all cases, their theoretical design loads of STM, ACI 318M-19 remained less than the experimental ultimate capacity by about 2.5-32.9%, 22.4-32.8% and 13.6-33.1%, respectively. That is why, it is possible to conclude that the STM of ACI 318M-19 is very effective in analyzing reinforced concrete ring deep beams, despite its conservatism.

It is worth to mention that the proposed specimens were less in weight and cost in addition to providing opening for services by about 10.28-29.61%, 4.04-20.01%, and 23.48-30.16%, respectively in comparison with the solid reference specimens. It is also worth to mention that increasing number of supports from 3 to 4, i.e. decreasing shear span/effective depth ratio (a/d) by 25%, leads to increase load capacity by about 13.6-47.6%.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF PLATES

LIST OF TABLES

LIST OF SYMBOLS AND TERMINOLOGY

SYMBOLS

a	Shear span measured from center of support to center of load, mm
A_h	Area of secondary horizontal reinforcement, mm^2
A_v	Area of secondary vertical reinforcement, mm^2
b	Width of cross section of ring deep beam, mm
d	Effective depth of beam, distance from extreme compression fiber to centroid of longitudinal tension reinforcement, mm
D	Diameter of ring specimen center to center, mm
E_c	Modulus of elasticity of concrete, MPa
E_s	Modulus of elasticity of steel reinforcement, MPa
f'_c	150mm×300mm Cylinder compressive strength of concrete, MPa
f_{ce}	Effective compressive strength of the concrete in a strut or a nodal zone, MPa
f_{ct}	Indirect tensile strength (splitting tensile strength), MPa
f_{cu}	Cube compressive strength of concrete
f_r	Modulus of rapture, MPa
f_y	Yield stress (MPa)
f_{yh}	Yield stress of secondary vertical reinforcement, MPa
f_{yv}	Yield stress of secondary horizontal reinforcement, MPa
F_n	The capacity of STM members, kN
h	Total depth of ring deep beam, mm
j_d	Moment arm, mm
L_b	Length of load bearing block, mm
$P_{c\text{-}exp}$	Experimental concrete strength, kN
$P_{cr-diag}$	First diagonal cracking load, kN
$P_{cr-flex}$	First flexural cracking load, kN
P_{exp}	Failure load of ring deep beam, kN
P_n	Nominal applied load, kN
P_{STM}	Theoretical load according to chapter 23, ACI 318M-14 Strut and Tie method, kN
S_h	Spacing of secondary horizontal reinforcement, mm
S_v	Spacing of secondary vertical reinforcement, mm
σ_{vB}	Ultimate stress of horizontal face of node, MPa
V_n	Nominal strength, kN
Ømain	Diameter of bar for main reinforcement, mm
Øst	Diameter of bar for shear reinforcement, mm
w_{sb}	Width of strut at support nodal zone , mm
w_{st}	Width of strut at load nodal zone, mm
w_t	Width of anchor tie, mm
α_1, α_2	Inclination angle of reinforcement to the axis of the ring deep beam, degree
β_c	Confinement modification factor for struts and nodes

β_n	Nodal zone coefficient
β_s	Factor to account for the cracking effect and confining reinforcement on the effective compressive strength of the concrete in a strut
Δ	Displacement corresponding to the ultimate of ring deep beam, mm
$\Delta_{cr-diag}$	Displacement corresponding to the 1st diagonal crack load, mm
$\Delta_{cr-flex}$	Displacement corresponding to the 1st flexural crack load, mm
Δ_L	Lateral displacement corresponding to the ultimate of ring deep beam, mm
ε_{yield}	Strain at yield
θ	Angle of inclination of the diagonal compressive stress and the failure plane with the ring deep beam longitudinal axis in right side, degree
ρ	Main reinforcement ratio
ρ_h	Secondary horizontal reinforcement ratio
ρ_v	Secondary vertical reinforcement ratio
ϕ	Diameter of bar, mm

TERMINOLOGY

a/d	Shear span to effective depth ratio
a/h	Shear span to overall depth ratio
L_n/h	Clear span to overall depth ratio
ACI	American Concrete Institute
ALWC	All Light Weight Concrete
ANSYS	Analysis System
ASTM	American Society for Testing and Materials
BS	British Standard
c/c	Center to center clear span, mm
Cc	Clear cover, mm
CCT	Compression- Compression- Tension
CDBFDA	Curved Deep Beam Finite Difference Analysis
CSA	Canadian Standard Association
EC2	Eurocode2
ECP	Egyptian Concrete Code of Practice
HSC	High Strength Concrete
I.Q.S	Iraqi Standard Specification
JSCE	Japan Society of Civil Engineers
NFHCBSL	Nonlinear Finite Element Analysis of Horizontal Curved Beam under Static Load
NLFEA	Nonlinear Finite Element Analysis
NSC	Normal Strength Concrete
NWC	Normal Weight Concrete
RC	Reinforced Concrete
SC	Strain of concrete surface
SCC	Self-Compacted Concrete
SLWC	Sand Light Weight Concrete
ST	Strain of steel
STM	Strut and Tie Model

CHAPTER ONE
INTRODUCTION

1.1 General

Curved members are back in the spotlight after Zaha Hadid's famous architectural rework. Architects and civil engineers re-evaluated curved beams from other perspectives. Noting that it is not new that it has been found advantageous to use horizontally curved beams or bow girders in building and bridge design. Arched in plan beams constructing considerably utilized for balcony in building, occasionally on the structure of the bridge and other structures. Meantime, domes, silos, circular tanks, offshore structures, and other structures use ring beams with a completely circular plan. Because of their high load resistance, industries have relied on ring deep beams (Al Qaicy, et al., 2014).

Beam members whose axis are curved in the plan are ordinary continuous and monolithic with columns in reinforced concrete building. Figure (1-1) shows examples of horizontally curved beams in a building construction. This building is called "The First Round Office Building in the World" (Lee, 1956).

Figure (1-1): Round Office Building, (Lee, 1956)

Deep beams, according to the ACI 318M-19 Code are defined as: "Structural Members supported on one face and loaded on the opposite face so that struts-similar compression elements can expand between the supports and the loads, that state (1) or (2):

1) The clear span of the beam must not be more than four times the overall depth of the beam ***h***.
2) Concentrated loads are those that occur within ***2h*** of the support face."

In mathematical forms, ($a/h \leq 2$) should be taken into consideration for simple span deep beams and continuous deep beams.

1.2 Modeling with Struts and Ties (STM)

Struts and Ties Modeling is a method of analyzing and designing the reinforced concrete deep structures and reinforced concrete deep prestressed structures. STM simplifies complex states of stress in a structure and suggests simple stress paths. The STM approach is based on the idea that any stresses within a deep structure are transported along valid and consistent paths from one point to another. The stress paths cause uniaxial stresses in suggested truss members. Truss members in compression are named struts, whereas the force paths in tension are called ties. The junctions of ties - struts are called nodes as shown in Figure (1-2). The combination of ties, struts and nodes is named a truss mechanism.

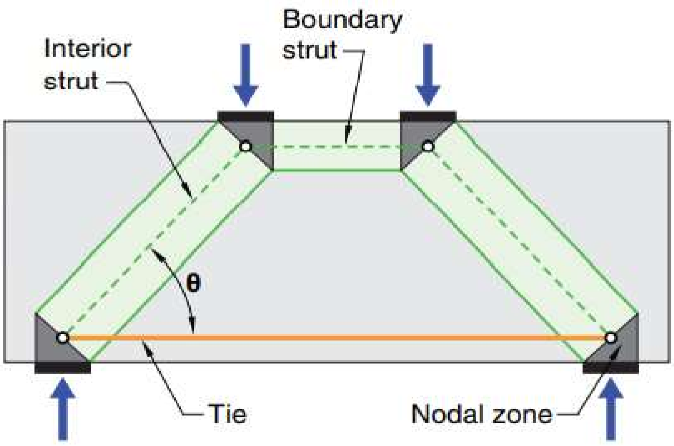
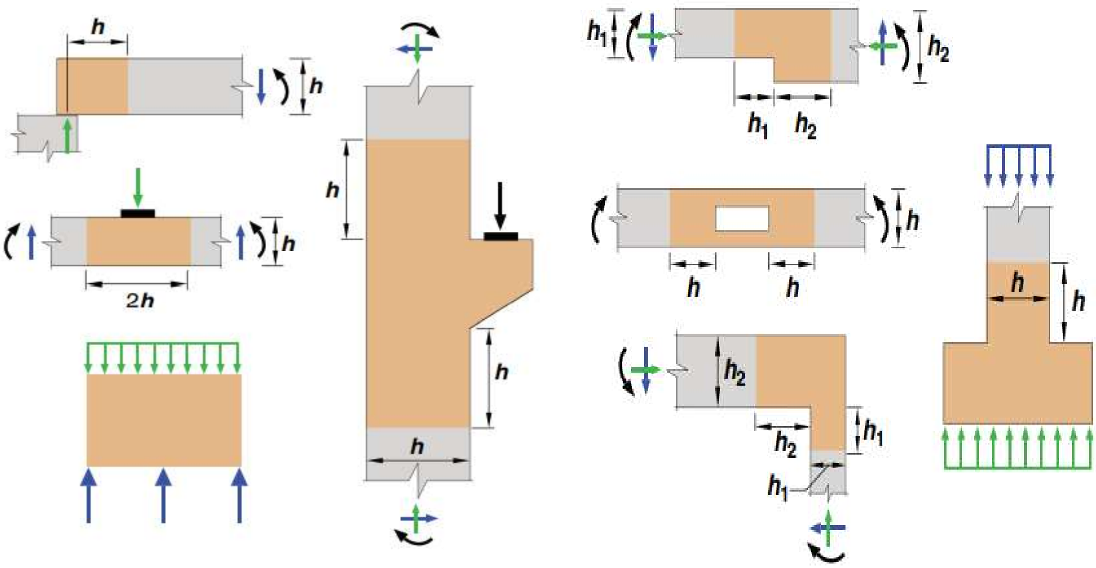


Figure (1-2): Description of strut and tie model, (ACI 318M-19)

Struts are the resultant of the stress fields which are compression chords of the truss mechanism. Struts are located diagonally through the structure and transfer shear to supports. When struts are located diagonally and transfer shear, a crack appears along the strut under loading. Within the analysis stage, node equilibrium and overall equilibrium are considered. Empirical observation of ties, struts, and nodes is used to determine the constitutive relevance of these elements in order to set the yield conditions for these elements. As a result, strut and tie models follow the lower-bound of plasticity theory, which states that only yield conditions and equilibrium must be persuaded (Brown and Bayrak, 2006). According to the lower-bound of plasticity theory, if the load is large enough to allow the discovery of a stress distribution that is identical to stresses at the yield surface while maintaining external and internal equilibrium, the load will not cause the body to collapse (Nielsen, et al., 1978). More specifically, the capacity of a structure will be at most to or less than the actual collapse load, as determined by an approach lower bound.

1.3 Regions of Discontinuities in Reinforced Concrete Members

When the geometry of the element in a structure or in a reaction or concentrated load is changed as shown in Figure (1-3), an abruption in the distribution of stresses exists at that change. Principle of St. Venant's states that the stresses, because of bending and axial load, have linear distribution at a distance approximately equals to member height far from the discontinuity. For this reason, discontinuities are described as extending h from the section that change in geometry or load (ACI 318M-19). Therefore, a structural element can be divided into the following regions:



Loading discontinuities Geometric discontinuities

Figure (1-3): Typical D regions, (ACI 318M-19, Chapter 23)

- ***B Regions:*** They are the parts of a member that can be used to solve the "plane section" assumptions of the conventional beam theory using a sectional design approach. In this region where the Bernoulli hypothesis of plane strain distribution is valid, a structure can be considered as a sectional block.
- ***D Regions:*** When the region in a structure includes nonlinearity such as concentrated load, corners, opening or other geometric discontinuities, the Bernoulli hypothesis can no longer be utilized for design or analysis. They're all the areas outside of the B zones where cross sectional planes don't stay plain after loading. When there are discontinuities or disturbances in the distribution of stress at parts of a structure member, D regions are commonly assumed (ACI 318M-19).

1.4 Elements of Strut and Tie Model

1.4.1 Struts

In strut-tie models, struts are the components that carry compressive stresses. The geometry of a strut is determined by the applied load type. According to Nielsen et al. (1978), there are three types of struts:

(a) ***Prismatic Strut:*** the most fundamental type of struts. The width of a prismatic strut is constant throughout its length, as shown in Figure (1-4). When the compressive stresses are limited by the neutral axis, such a strut can exist in a beam. A prismatic strut is a representation of a beam's compressive stress block in a section of constant moment (Brown and Bayrak, 2006).

(b) ***Bottle-Shaped Strut:*** A bottle-shaped strut can be developed because the compressive stresses flow is not restricted to a part of a structural element, as shown in Figure (1-4). The load is applied to a small area in this case, as stress flows through the member, it dissipates. The stress changes direction when it divides and forms an angle with the axis of the strut. In order to maintain equilibrium, a tensile force is developed to prevent the lateral component of the angled compression forces.

(c) ***Compression Fan Strut:*** It is specialized due to the fact that it focuses care on such a small area. Stresses cause a radial flow from a large to a smaller area. When large uniform loads flow into a support, a compression fan is formed, as shown in Figure (1-4). Because the forces are collinear and there are no tension components perpendicular to the fan zone, the tensile stresses developed have no value (Brown and Bayrak, 2006).

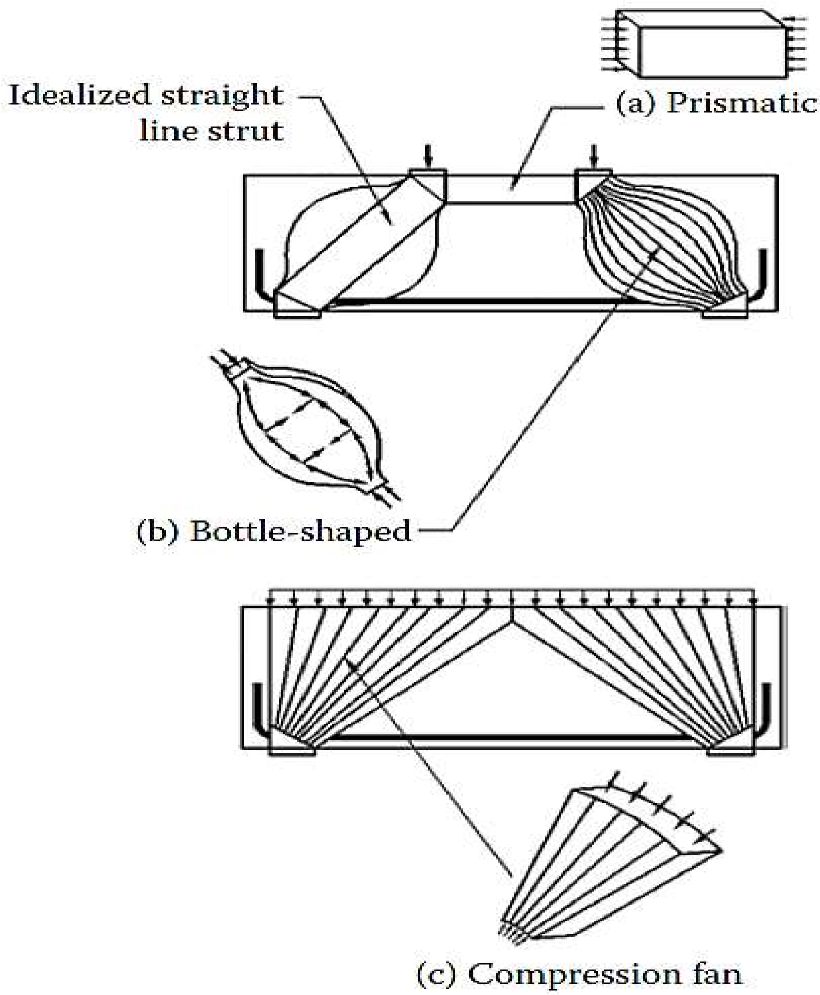


Figure (1-4): Geometric shapes of struts,(El-Metwally and Chen, 2018)

1.4.2 Ties

Ties are the elements that carry tension, are mostly restricted to reinforcing. Therefore, the geometry of a tie is so simpler than the strut or the node. Geometrically, the tie is limited to elements can carry high tensile strengths, and the allowed force is derived mainly from the yield force.

Ties are made up of deformed rebar, prestressing rebar, or both, as well as an enclosure concrete section concentric to the axis of the tie. The model almost never considers that the enclosure concrete can stand axial force. While the elongation of the tie is reduced, the strain in the tie, which under service loads is particularly useful, is also strengthened. The area where the ties and struts are to be anchored is also specified.

1.4.3 Nodes

Nodes are the points at which the strut axes, ties and concentrated forces intersect, representing the joints of a strut and tie model (ACI 318M-19). The location at which forces are redirected within a strut and tie modeling is another way of defining a node. To maintain equilibrium, at least three forces should be acting on a given node of the model, on the basis of the forces that act on them, nodes are listed as follows (Fu, 2001):

- C-C-C: that implies the node that resists three compression forces.
- C-C-T: that implies the node that resists two compression forces and one tensile force.
- C-T-T: that implies the node that resists one compression force and two tensile forces.
- T-T-T: that implies the node that resists three tensile forces.
- C-C-C-T-T: that implies the node that resists three compression forces and two tensile forces (internal node in a continuous deep member).

The amount of concrete presumed to transfer strut and tie forces through the node is referred to as the nodal region, Figure (1-5). The early strut and tie models used hydrostatic nodal zones, which have recently been supplanted by extended nodal zones. The hydrostatic term means that in all directions, the stress of the plane is the same.

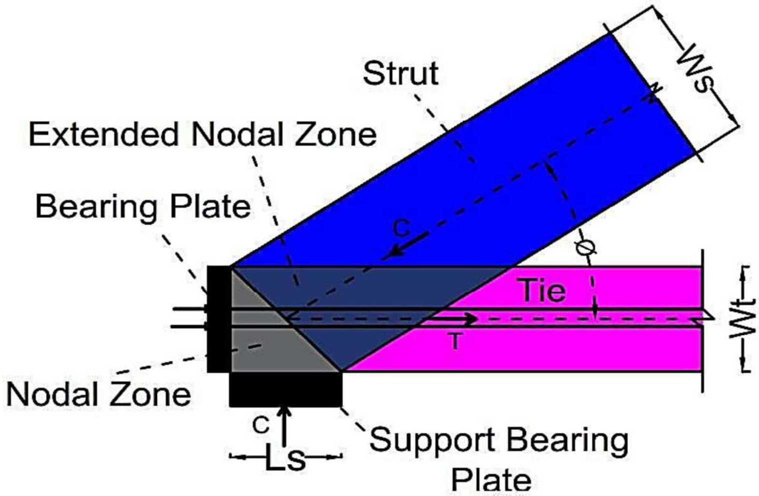
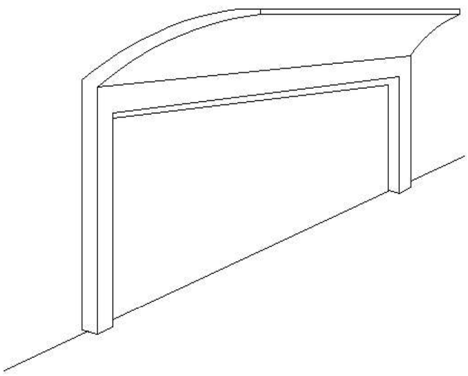


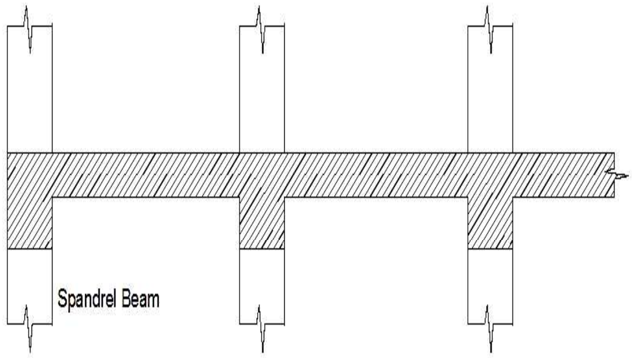
Figure (1-5): Nodal and extended nodal zones, (Brown and Bayrak, 2006)

1.5 Torsion in Reinforced Concrete Members

When the external loads are applied at a distance from the vertical bending plane, or beam subjected of the twisting about its longitudinal axis, the beam behaves as a torsional member, in addition, shearing force and bending moment. Figure (1-6) shows two examples on the members subjected to twisting moment (Ghoeim, Mihilmy, 2007).



(a)



(b)

Figure (1-6): (a) Cantilever canopy, (b) Spandrel beam, (Ghoeim, Mihilmy, 2007)

In reinforced concrete structures, the torsion can be classified into two main types; primary torsion, usually called equilibrium torsion, exists in the case of supporting the external load by the torsional moment. The torsional moments play a role in achieving the equilibrium such as the cantilever slabs. The applied load to the slabs surface causes torsional moments that act along the span of the supported beam. They are equated by the internal resistance torque supplied at the columns.

The second type of torsion is called secondary torsion, also named statically indeterminate torsion which exists between adjacent members of structure. In this case, an internal resistance arises from the requirements of continuity. Neglecting the continuity in the design and analysis will lead to significantly cracking, but this will not lead to collapse. An application of secondary torsion can be seen in the edge beam supporting concrete panel.

If the edge beam has small torsional stiffness and does not contain torsional reinforcement, the cracks will occur and cause reduction in torsional stiffness and the slab edges will work as a hinged edge. If the moment is taken into account in design, the collapse will not occur (McCormac, et al. 2014).

1.6 Horizontally Curved Beams

The horizontally curved beam, unlike a straight beam, the neutral axis and the centroidal axis are not coincident of a horizontal curved beam. Furthermore, stresses do not vary linearly from the neutral axis (Anderson, et al. 1950). In horizontally curved beam, torsional moments occur because the reactions and the applied loads do not lie over the main axis along the curved beam. These torsional moments become zero at the midspan between any two successive columns in case of a circular beam that supported by equally spaced columns. Maximum torsional moments grow at sections closer to the supports in addition to the zones where the bending moment is zero, the maximum torque takes place at the points of contraflexure as shown in Figure (1-7). Furthermore, at sections between the supports, positive maximum bending moments develop, while, the maximum negative bending moments occur at the support sections. As for the shear forces, they are maximum at the support sections.

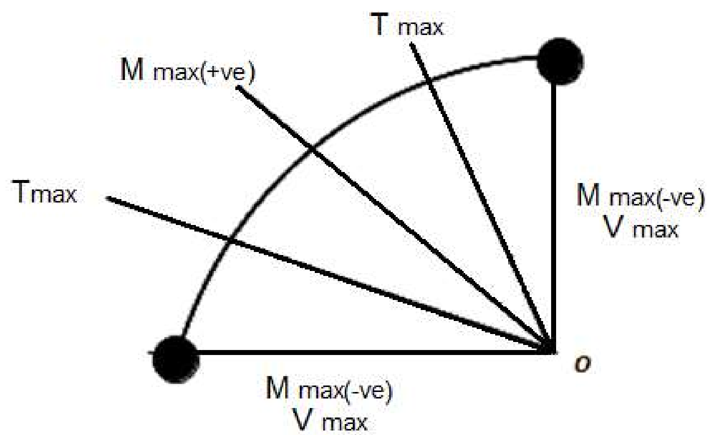


Figure (1-7): Maximum moments and shear locations in curved beam segment, (Anderson et al. 1950)

The difference in design and analysis between the straight beams and the in-plan horizontally curved beams is fundamentally because of the presence of torsional movements caused by vertical load. Therefore, for such members, it is important to design both the twisting moments and the internal bending moments as well as the transverse shear. The capability of resisting torsional moment is expressed by torsional rigidity. That is defined as the torsional moment, which, when applied to one free to rotate end, produces a unit angle of twist with respect to the other end assumed to be completely fixed (Andersen, et al.1953). The greater the torsional rigidity, the greater the resistance to the torque. The value of torsional rigidity depends on the shape of the section. It was found that the box sections have comparatively large values of torsional rigidity (Iyse, I., 1941) and, that is why are widely used in bridge design. However, the rectangular section is also commonly used.

1.7 Objectives of the current study

The main objective of the present work is to investigate the behavior of reinforced concrete ring deep beams through using STM of ACI 318M-19, especially when reinforcing the stress paths of the struts and ties. In other words, omitting of the concrete zones that are not located in the stress paths of the struts and ties. Thus, that leads to a decrease in weight and saving in cost while keeping the same theoretical design load of STM, ACI 318M-19.

1.8 Layout of the Thesis

The current thesis consists of five chapters which can be summarized as follows:

- **Chapter One** presents a general introduction about RC deep ring beams, STM, horizontal curved beam, analysis of ring deep beam, and the study objectives.

- **Chapter Two** presents a review of some experimental, theoretical and numerical previous research works that are achieved on reinforced concrete deep ring beams, horizontally curved beams, curved continuous deep beams in addition to the validation of STM.
- **Chapter Three** deals with the properties of the utilized construction materials in addition to the experimental work plan.
- **Chapter Four** deals with the test results of specimens, evaluating and discussing the experimental results of the current study.
- **Chapter Five** provides the main conclusions drawn from the current study, recommendations, and suggestions for further studies.