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BEHAVIOR OF REINFORCED CONCRETE ELLIPTICAL RING DEEP BEAMS

A Thesis Submitted to Council of College of Engineering,
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Requirements for the Degree of Master of Science in
Structural Engineering

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CHAPTER ONE

INTRODUCTION

1.1 General

Zaha Hadid, the British architect (born in Iraq) has once again transformed the curves to express modernity in contemporary life, using them with all intelligence and boldness to express the conscience of current humanity, and perhaps the future as well. She used them in residential and public buildings, airports train stations, even in sports facilities and stadiums...etc. This would not have been achieved without the effective response of the structural engineering, in which the handling of curves became more accurate and rapid as well.

As was already said above, curved members are once again in the limelight. Curved beams were re-examined by structural engineers and architects from many angles. Noting that the usage of horizontally bent beams or bow girders in building and bridge construction has long been considered desirable. Beams with an arched design are frequently used for balconies in construction and also in bridge and other structure construction. In the meanwhile, entirely ring beams are used in domes, silos, tanks, offshore buildings, and other constructions. Ring deep beams have been used by businesses because of its great load resistance (Al Qaicy, et al., 2014).

Beam members in a reinforced concrete structure with curved axis are regular continuous and monolithic with columns. Examples of horizontally curved beams used in building construction are shown in Figure (1-1), "Capitol Records Building" (Lee, 1956).

Figure (1-1): Capitol Records Building" (Lee, 1956)

It is well known that the deep beam is distinguished from the traditional shallow beam by its great height compared to its span, which causes a non-linear distribution of the strains along its height. This non-linearity prevented the possibility of using the traditional theorems and equations that structural engineers are accustomed to, so they resorted to other methods, for example, the Strut and Tie Modelling (STM). That is, the stresses are transmitted directly from the loading to supporting points through the compression members (struts) that meet the tension members (ties) at specific points (nodes) (ACI 318M-19 Code). Nonetheless in the case of a horizontal curvature, the above-mentioned stresses will be added to the torsional stresses that were formed as a result of the mismatch of the load points and the supporting points on a straight line, which increased the complexity of the issue, so this study was conducted.

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 and 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

The principle of St. Venant asserts that the strains caused by a discontinuity in the load or a change in the characteristics of the section is nonlinear at distances greater than or equal to the height h from the point of loading. Saint Venant's principle does not apply to points closer than the distance h at which there is a discontinuation of the load or a dimension change. This leads to the formation of the discontinuation zones within the reinforced concrete members near the concentrated loads, openings, and dimension change. In such a case, concrete members can be divided into two zones, the first in which Bernoulli's theory applies, they are called B regions (Bernoulli), and the zones in which interruptions affect the behavior of members are D regions (Discontinuity or Disturbance), (ACI 318M-19 Code).

At low compressive stresses, when the concrete is not cracked, i.e. elastic, it is possible to resort to the theory of elasticity, where it is possible to calculate the stresses within B regions, but when the concrete cracks, this stress field will be disrupted, leading to a redistribution of internal forces. When this occurs, it is possible to represent the internal forces truss-like, referred to as the strut-and-tie model (STM), Figure (1-2). STM is the approach of analyzing reinforced concrete structures and prestressed reinforced concrete structures because it transforms complex stresses into simple stress pathways; compression and tension that meet at the nodes, (Brown and Bayrak, 2006).

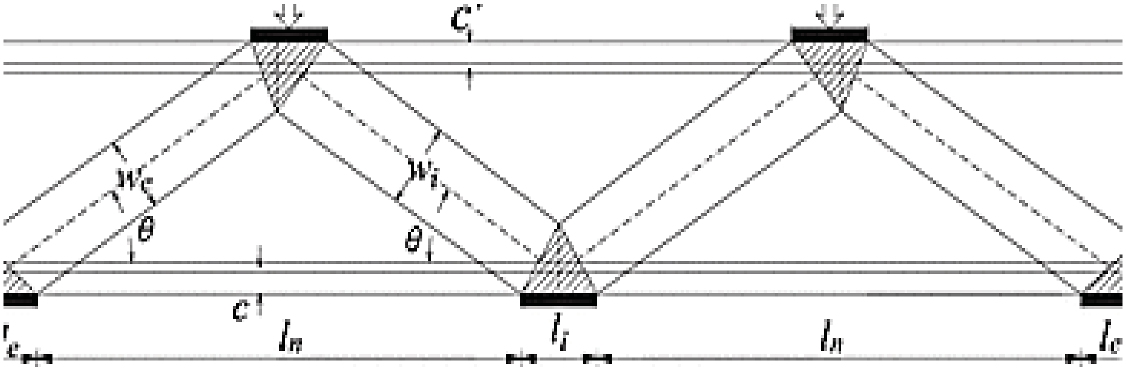


Figure (1-2): Truss-like assumption of Strut and Tie modelling, (Brown and Bayrak, 2006)

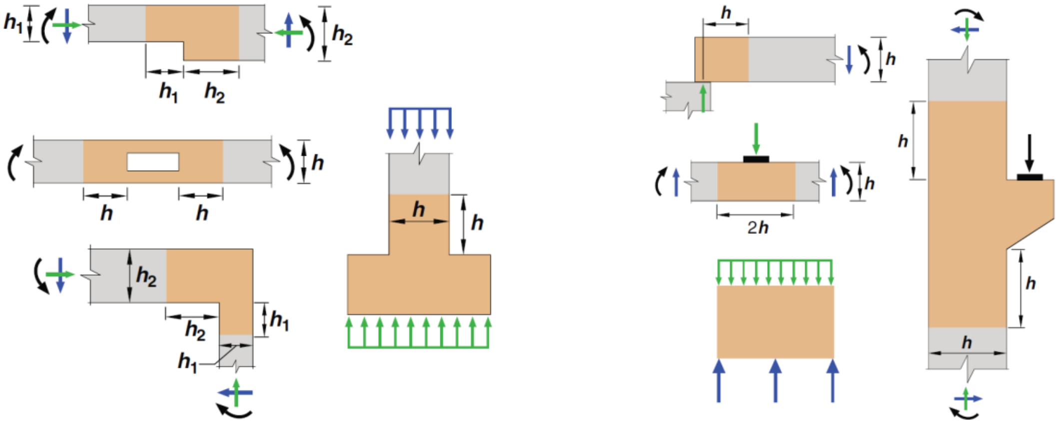
The constitutive relevance of struts, ties, and nodes is determined by empirical observation in order to specify the yield conditions for these parts. As a result, strut and tie models adhere to plasticity theory's lower bound, which implies that only yield conditions and equilibrium must be persuaded (Brown and Bayrak, 2006).

Based on the plasticity theory lower-bound, if the applied load is sufficient great to permit the stress distribution discovery that is identical to yield surface stresses at the while maintaining internal and external equilibrium, the load would not lead the body to fail (Nielsen, et al., 1978). More specifically, the structure load capacity will be at most to or less than the real load of failure, as calculated by a lower bound approach.

1.3 Discontinuity Regions in Reinforced Concrete Members

An abruption in the distribution of stresses occurs when the geometry of an element in a structure, a reaction, or a concentrated load is changed, as shown in Figure (1-3). According to the St. Venant's principle, stresses caused by bending and axial load have a linear distribution at a distance equal to the member height away from the discontinuity. As a result, discontinuities are defined as extending h from the region where the geometry or load changes (ACI 318M-19 Code). Consequently, a structural element will contain the following regions:

- **B Regions:** These are the regions of a component that may be employed in a sectional design technique to solve the "plane section" assumptions of traditional beam theory. A structure can be regarded a sectional block in this region where the Bernoulli hypothesis of plane strain distribution is valid.
- **D Regions:** The Bernoulli hypothesis can no longer be used for design or analysis when a region in a structure contains nonlinearity such as concentrated load, corners, openings, or other geometric discontinuities. Outside of the B regions, they're all the zones where cross sectional planes don't stay linear after loading. D regions are typically considered when there are discontinuities or disruptions in the distribution of stress at different zones of a structural member (ACI 318M-19).



(a) Geometric discontinuities (b) Loading and geometric discontinuities

Figure (1-3): B and D regions, (ACI 318M-19 Code)

1.4 Strut and Tie Modelling

1.4.1 Struts

Struts are the components that bear compressive loads in strut-tie models. The applied load type determines the shape of a strut. There are three types of struts, according to Nielsen et al. (1978):

(a) Prismatic Strut: The most basic sort of strut is the prismatic strut. As seen in Figure (1-4), the breadth of a prismatic strut remains constant throughout its length. In a beam, such a strut can exist when the compressive stresses are confined by the neutral axis. In a section with constant moment, a prismatic strut represents the compressive stress block of a beam. (Brown and Bayrak, 2006).

(b) Bottle-shape Strut: Because the compressive stresses flow is not constrained to a component of a structural member, a bottle-shaped strut can be produced, as illustrated in Figure (1-4). In this situation, the load is delivered to a limited location, and the stress diminishes as it passes through the member. When the stress splits and creates an angle with the strut's axis, it changes direction. A tensile force is created to prevent the lateral component of the angled compression pressures from causing instability.

(c) Compression Fan Strut: Because it concentrates attention on such a limited region, it is specialized. A radial flow from a big to a smaller region is caused by stress. A compression fan is generated when huge homogeneous loads flow into a support, as seen in Figure (1-4). The tensile stresses created have no importance since the forces are collinear and there are no tension components perpendicular to the fan zone (Brown and Bayrak, 2006).

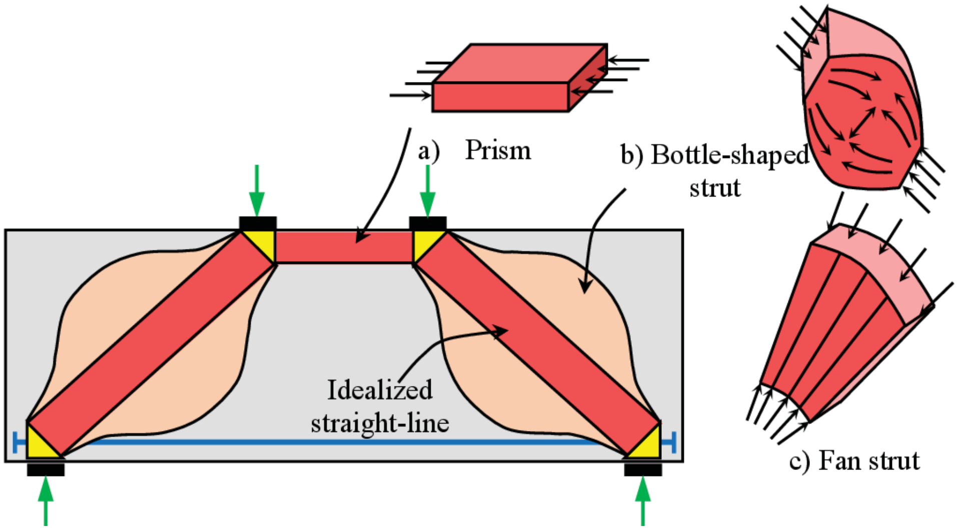


Figure (1-4): Types of struts, (Mohamed, 2015)

1.4.2 Ties:

Ties are tension-carrying components that are usually used for strengthening. As a result, the geometry of a tie is much simpler than the geometry of a strut or a node. The tie is geometrically limited to components with high tensile strengths, and the permitted force is mostly determined from the steel yield strength. Deformed bars, prestressing bars, or both, as well as a concrete enclosure section concentric to the tie's axis, make up ties. The STM virtually does not take into account the ability of the enclosing concrete to withstand axial tensile force. While the tie's elongation is reduced, the strain in the tie is reinforced, which is especially advantageous under service loads. It is also specified where the ties and struts will be anchored.

1.4.3 Nodes:

The joints of a strut and tie model are represented by nodes, which are the zones where the strut axis, ties, and concentrated forces intersect (ACI 318M-19). Another method to define a node is the place where forces are diverted inside a strut and tie modelling. At least three forces should be acting on each node of the model to preserve equilibrium; nodes are listed as follows, (Fu, 2001), based on the forces that act on them:

1- C-C-C: forms when three compressive forces meet.
2- C-C-T: forms when two compressive forces and one tensile force meet.
3- C-T-T: forms when one compressive force and two tensile forces meet.
4- T-T-T: forms when three tensile forces meet.
5- T-T-C-C-C: forms when three compressive forces and two tensile forces meet.

The nodal zone is the quantity of concrete assumed to transfer strut and tie forces through the node, as shown in Figure (1-5). Hydrostatic nodal zones were utilized in early strut and tie models, however they have lately been replaced by expanded nodal zones. The word "hydrostatic" refers to the plane's stress being the same in all directions.

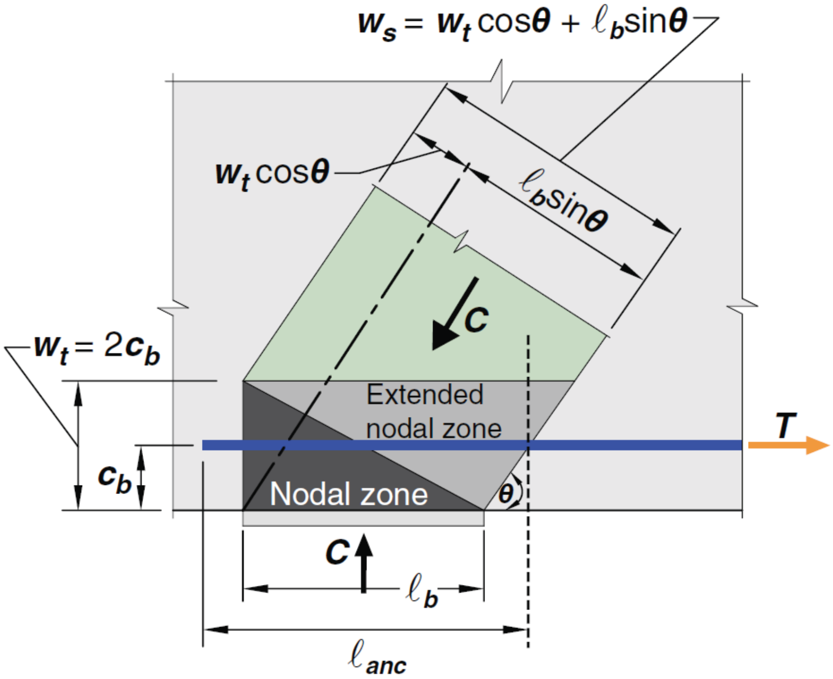


Figure (1-5): Nodal and extended nodal zones, (ACI 318M-19)

1.5 Horizontal Curved Beams

In contrast to a straight beam, the neutral axis and the centroidal axis of a horizontally curved beam are not coincident. Furthermore, from the neutral axis, stresses do not change linearly (Anderson, G., 1950). Torsional moments arise in horizontally curved beams because the reactions and applied loads do not lay across the main axis of the curved beam. In the case of an elliptical beam supported by evenly spaced columns, these torsional moments become zero at the midspan between any two succeeding applied loads. In addition to the zones where the bending moment is zero, maximum torsional moments develop at sections closer to the supports, and maximum torque occurs at the sites of contraflexure, as illustrated in Figure (1-6). Furthermore, positive maximum bending moments appear between the supports, whereas maximum negative bending moments occur at the support sections. Shear stresses are at their highest in the support zones.

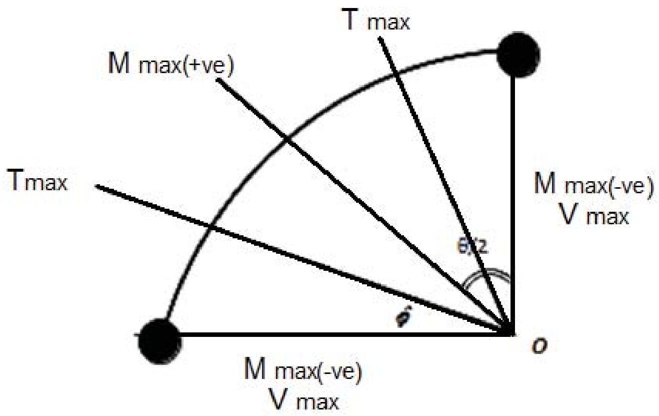
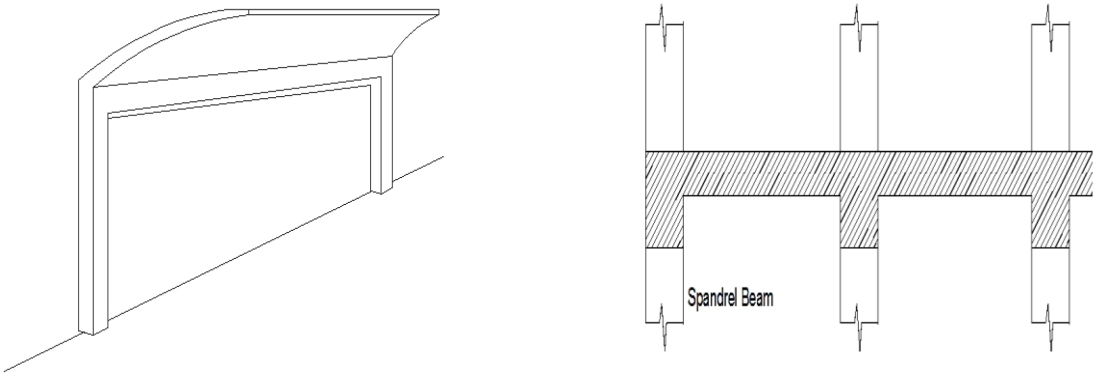


Figure (1-6): Maximum moments and shear locations in a horizontally curved beam segment

The existence of torsional deformations generated by vertical load causes a difference in design and analysis between straight beams and in-plan horizontally curved beams. As a result, it is critical to design both the twisting and internal bending moments, as well as the transverse shear, for such members. Torsion stiffness is a measure of a material's capacity to resist a torsional moment. That is defined as the torsional moment that causes a unit angle of twist with regard to the other end considered to be entirely stationary when supplied to one free to rotate end (Andersen, P., 1953). The torque resistance increases as the torsional stiffness increases. The value of torsional stiffness is determined by the section's form.

1.6 Torsion in Reinforced Concrete Members

The behavior of the beam affected due to torsional, shearing force and bending moments, when the external loads are applied away from the vertical bending plane or when the beam is subjected to twisting about its longitudinal axis. Two instances of members exposed to a twisting moment are shown in Figure (1-7). (Ghoeim, Mihilmy, 2008).



(a) (b)

Figure (1-7): (a) Cantilever canopy, (b) Spandrel beam (Ghoeim, Mihilmy, 2008)

Torsion in reinforced concrete structures may be divided into two basic categories: **primary torsion**, also known as **equilibrium torsion**, occurs when a torsional moment is used to sustain an external load, Figure (1-7a). As with cantilever slabs, the torsional moments play a part in establishing stability. Torsional moments are produced by the applied load to the slab's surface and act along the supporting beam's span. The internal resistance torque applied at the columns is used to equal them.

Secondary torsion, also known as **statically indeterminate torsion**, is the second kind of torsion that can occur between structurally neighboring elements. In this instance, internal resistance develops as a result of the need for continuity. Even if severe cracking will result from neglecting the continuity in the design and analysis, the structure won't collapse. The concrete panel that supports the edge beam exhibits secondary torsion, Figure (1-7b).

If the edge beam lacks torsional reinforcement and has a low torsional stiffness, fractures will form, reducing the torsional stiffness and causing the slab edges to function as hinged edges. The collapse won't happen if the moment is taken into consideration during design (Maccormac et al. 2014).

1.7 ETABS 2018 Finite Element Analysis

The ETABS Finite Element software was utilized to analyze the reinforced concrete ring deep beam in this case. The FEA (Finite element Analysis) for estimating how the ring beam reacts to experimental final loads is computerized here. The FEA is used by ETABS to divide an actual reinforced concrete ring deep beam into a large number of finite elements for analysis. Modeling tools and templates, load characterization using the ACI 318 code, analysis and/or solution techniques, and all coordination in this structural class with grid-like geometry are all included in the ETABS software. The values of the reactions at the supports, the negative moments, the positive moments and the torsional moments were all obtained. This software was also used in truss analysis of the Strut and Tie modelling of the ACI 318M-19.

1.8 Reinforcement limitations

1.8.1 Secondary reinforcement limitations

Deep beams' side faces and secondary reinforcement distribution must meet the criteria in (a) and (b) of ACI 318-19, 9.9.3.1 at minimum:

(a) The “distributed reinforcement area normal to the longitudinal beam axis, $\mathbf{A_v}$, shall be at least $\mathbf{0.0025b_w s}$, provided that the spacing of the distributed transverse reinforcement is **s**”.

(b) The “distributed reinforcement area parallel to the longitudinal axis of the beam, $\mathbf{A_{vh}}$, shall be at least $\mathbf{0.0025b_w s_2}$, where $\mathbf{s_2}$ is the spacing of the longitudinal reinforcement distribution". The spacing of the necessary distributed reinforcement shall not exceed less than 12 in and d/5 (ACI 318-19, 9.9.4.3).

1.8.2 Main reinforcement limitations

For a statically determined beam, the greater of (a) and (b) is the minimum flexural tension reinforcement area, $\mathbf{A_{s,min}}$ (ACI 318M-19, 9.9.3.2):

(a) $\frac{0.25\sqrt{f'c}}{F_y} b_w d$ ------------ (1-1)

(b) $\frac{1.4}{F_y} b_w d$ ------------ (1-2)

1.8.3 Concrete cover limitations

The minimum concrete cover required for fire protection is 75 mm maximum and 10 mm minimum, unless the general construction code stipulates a larger concrete cover (ACI 318M-19, 20.5.1.1):

1.9 Objectives of the study

Studying the behavior and strength of elliptical reinforced concrete deep beams by changing the most important parameters that influence them. As it is known that the stresses are transmitted directly from loading to supporting points by means of concrete compressive members (struts) that meet the tensile members (ties) in the nodes, which is called Strut-and-Tie Modelling (STM). STM does not take into account the torsional stresses caused by the horizontal curvature, nor does it take into account the flexural stresses formed in the strut itself as a result of its curvature. In addition, only the paths of the STM were cast here in order to study those paths and to determine their compatibility with the practical reality. The elliptical beams are distinguished from the circular ones by the lack of symmetry in its struts due to the presence of two axes: major and minor (not one radius as in the circle), which raised more questions that were additional reasons for conducting this study.

1.10 Thesis Layout

The current thesis is divided into five chapters, each of which contains the following information:

- **Chapter One** provides an overview of RC elliptical ring deep beams, STM, horizontal curvature in deep beams, finite element analysis of elliptical ring deep beams, reinforcement limitations and the study objectives in addition to thesis layout.
- **Chapter Two** offers a review of some prior research activities concerning experimental investigations on RC ring deep beams, horizontally curved beams, continuous deep beams and STM validation.
- The qualities of the used building materials, as well as the experimental work plan, are detailed in **Chapter Three**.
- **Chapter Four** focuses on providing laboratory specimen test findings, as well as assessing and discussing the current study's experimental outcomes.
- The primary concluded remarks gained from the current study, as well as recommendations and proposals for future research, are presented in **Chapter Five.**

Behavior of Reinforced Concrete Elliptical Ring Deep Beams

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ABSTRACT

The main objective of the current study is the laboratory investigation of the behavior of reinforced concrete elliptical ring deep beams using the Strut and Tie Modelling (STM) of the ACI 318M-19. In addition, studying the behavior and strength of a proposed frame specimen in which only STM stress paths were cast and reinforced. This study included casting and testing eleven laboratory specimens divided into four groups. The section width of all specimens was 100 mm, while the height was changed between 300 mm and 350 mm. The main (major) diameter was 1500 mm and the secondary (minor) diameter was 950 mm c/c. All specimens were rest on four supports, tested using single concentrated midspan loads.

The parameters considered are secondary web reinforcement, main reinforcement, beam height in addition to the efficacy of using the STM, ACI 318M-19 method with this type of curved deep beams. The first group included omitting the horizontal web secondary reinforcement, omitting the vertical web secondary reinforcement, and omitting them together, in addition to changing the diameter of the web secondary reinforcement from 4 mm to 8 mm. The second group included reducing the amount of main reinforcing steel by 55.6% and 100%. As for the third group, it included reducing the height from 350 mm to 300 mm, i.e. 14% height reduction. As for the fourth group, it contained three specimens; the first specimen was without reinforcement, the second was a proposed structure (frame) in which only the struts and ties were reinforced, while the third was a frame in which only the ties were reinforced.

The experimental failure load, the load-midspan deflection response, the load of the first crack and the amount of deflection at it, and the characteristics of the cracks in terms of type, width and propagation were investigated. The strain values were also investigated in critical locations of concrete surfaces and reinforcing steel bars. The deflection at the failure load was also investigated, in addition to the failure modes.

It has been concluded that the secondary and main reinforcement, in addition to the height of the beam section, have a significant role in the behavior and load capacity of such type of beams. In more detail, the absence of horizontal web secondary reinforcement led to a decrease of the failure load by 23.93% and a rise of the deflection by 63%. Also, the absence of vertical secondary web reinforcement led to a decrease in the failure load by 38% and the deflection by 66.67%. While the absence of secondary web reinforcement, both horizontal and vertical, led to a decrease in the failure load by 63.5% and the deflection by 33.4%. On the other hand, changing the web secondary reinforcing steel from a diameter of 4 mm to 8 mm led to an increase in the failure load by 8.5% and the deflection by 77%. Similarly, reducing the main reinforcement from diameter 12 mm to 8 mm or completely omitting it led to a decrease in the failure load by 10.11% and 48.4% in addition to a decrease in the deflection by 29.28% and 19.5%, respectively. As for the effect of reducing the beam height by 14%, it led to a decrease in the failure load and the deflection by 29.5% and 50.1%, respectively. Nonetheless, when the concrete was omitted outside the STM, ACI 318M-19 stress paths with reinforcing them as compressive and tensile members, the failure load of the proposed frame was less in the laboratory by 54.8% despite its superiority over the theoretical load of the STM, ACI 318M-19 by 23.2%, which made it a good alternative to the reference, especially that it is less weight by 21.48% and provides openings for services by 21%.

Finally, it was concluded here that using the STM, ACI 318M-19 to analyze such type of horizontally curved deep beams, although - that is, STM - does not take into account the curvature of the struts or the ties, but the realistic stress flow like in straight deep members on the one hand, and the small non-ruling torsional cracks on the other hand, made it an easy and safe method despite its reservations.