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BEHAVIOR OF REINFORCED CONCRETE DEEP BOX GIRDERS

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

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CHAPTER ONE

INTRODUCTION

1.1 General

A superstructure that connects the two sides is the bridge. It typically crosses a road or railroad by a natural or man-made barrier (Hemalatha, et al., 2021). A bridge is a structure that allows traffic to cross over an obstruction without blocking the way below. The required crossing might be for a pipe, canal, rail, pedestrian, or vehicle (Reyaz and Fathima, 2018). The bridge is the most responsible building for ensuring that traffic may move freely (Thakai, et al., 2016). The conventional bridge has been replaced by a creative, cost-effective structural design as technology has advanced swiftly. The concrete box girder is one of these techniques (miller, et al., 1999) and (hanna , et al., 2011). For bridges with short, medium, or long spans, adjacent precast, prestressed concrete box girders are a good option since they can be constructed fast and easy (Sennah and Kennedy, 2002) and (K Chaitanya, 2019).

The box often has a trapezoidal or rectangular cross shape. It constructed from two web plates joined at the top and bottom by flanges that are the same. Based on their design, intended function, and form, box girders can be divided into different groups. In actual life, there are three types of box girders that are often used. Single cells, double cells, and multiple cells can all be used in its construction and production. The concrete box girders are segmented precast or cast in place (Wang and Huang, 1994) as shown in Figure (1-1).

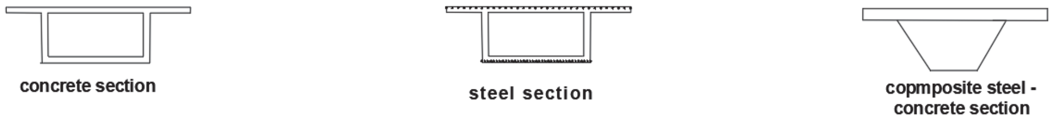


Figure (1-1a): Type of single cell Box Bridge

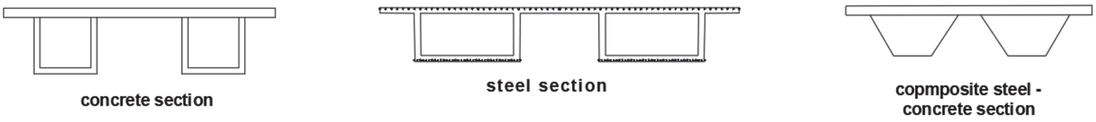


Figure (1-1b): Type of multi spin cell Box

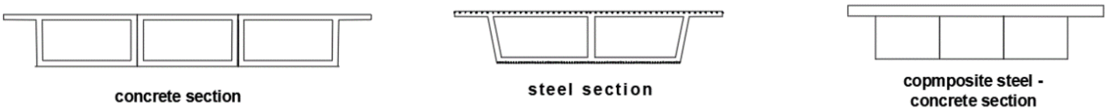


Figure (1-1c): Type of multi spin cell Box Bridge

Figure (1-1): Box Girder Bridges

Pre-stressed concrete, structural steel, or reinforced concrete are frequently used in box girder construction and it's may be segment precast or cast in place, plate (1-1), "cast in place deep box girder" (K Chaitanya, 2019).

plate (1-1): Cast in place deep box girder" (K Chaitanya, 2019)

1.1.1 Advantage of Box Girder

There are many advantages of using box girders, some of which can be listed below:

1- Due to their structural efficacy, improved stability, serviceability, cost-effective construction, and appealing aesthetics, box girder have become widely employed in highway and bridge systems (Agarwal, et al., 2020)

2- To reduce the dead load and lower construction besides material costs, box concrete sections are frequently utilized as beams, especially for long span bridges (Hemzah, et al., 2020). This type of bridge resists bending exceptionally well, especially due to its large bottom flanges.

3- The hollow parts of the box girder can also be used for utilities like sewers, telephone lines, electric supply cables, and water supply pipes. The section also has the benefit of being a lightweight construction (Bhagwat, et al., 2017).

4- Under eccentric loads, box girder has better load distribution due to its high ability to resist torsional moments (Lin and Yoda, 2017).

5- The closed section of the box girders' high torsional strength and rigidity make it easier for them to resist torsional moments brought on by curved alignments (Rodriguez, 2004).

6- In the interior central zone, it is simpler to maintain the massive box girder since it is directly accessible without the need for scaffolding.

7- Because the box girder contains top and bottom flanges, it is strong against positive and negative bending moments (García-Segura, et al., 2015).

8- The internal space is hermetically sealed, and the air inside can be dried to create a non-corrosive environment.

1.1.2 Disadvantage of Using Box Girders

There is no type of structure that contains only advantages, but also contains disadvantages. The evaluation depends on the extent of the actual need of the structure and the circumstances of its use. Some disadvantages are:

1- Manufacturing costs are higher for this type of normal beam than for other types (Rombach, 2002).
2- Instillation requires heavy machinery.
3- Inefficiencies in logistics and transportation may lead to additional cost (Ahmad, et al., 2017)

1.2 Deep Members

Because the deep box girder is a type of beams, an idea must be given here about the deep beams. It's well-known that the deep beam is any beam with a depth to span ratio high enough to produce non-parabolic shear stress distribution and non-linear elastic flexural stresses throughout the depth. The usual theorems and equations that structural engineers are used to utilize could not be used because of this non-linearity. Therefore, engineers turned to other methodologies like the Strut and Tie Modelling (STM). In other words, according to the ACI 318M-19 Code, the stresses are transferred directly from the loading to the supporting points through the compression members (struts) that connect to the tension members (ties) at particular connections (nodes).

Deep beam is defined as follows by the American Concrete Institute Code (ACI), (ACI Committee 318M, 2019):

Member supported on one surface while being subjected to loads on the opposite surface, allowing for the growth of compression struts between the locations of load and support. Deep beam only offers either of these:

a- Clear spans L_n is less than or equal to four times the depth of the entire member $L_n \leq 4h$; or b- shear span zones that are twice as deep as the support face of the member, ($a/h \leq 2$) in mathematical formulas.

For deep beams that are uniformly loaded, the critical section for shear should be obtained at a distance of ($0.15L_n \leq d$) from the face of support, and at a distance of ($0.5a \leq d$) for deep beams that are concentrated with loads. It should be known that (d) is the distance from the extreme compression surface to the centroid of tension reinforcement, (L_n) is the clear span, and (a) is the shear span, or the distance from the concentrated load to the face of the support. The span should be reinforced with shear where necessary in the critical portion (Merritt and Ricketts, 2001).

The deep beams made of reinforced concrete (RC) are critical structural members used in many different types of concrete structures. They can be identified by the fact that they are often deep and have a thin thickness in comparison to their length or depth. Pile caps, tanks, transfer girders, shear walls, foundation walls, folding plates of roofs, and offshore constructions are a few examples of common applications for deep members, receiving numerous little loads frequently in their own plane and transferring them to a limited reaction points number (Ashour and Yang, 2008).

1.2.1 Failure Modes of RC Deep Beams

Clear span/depth ratio (L_n/d), shear span/depth ratio (a/d), 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. are just a few of the parameters that affect the behavior and strength of deep beams (Subedi et al., 1986).

The failure of deep beams can be summed up as follows: (ACI-ASCE Task Committee 426, 1973):

1. **Flexural failure**: As shown in Figure (1-2), when a beam has a large a/h ratio and a low percentage of tensile steel, it fails by the steel reinforcement yielding at the maximum moment zone.

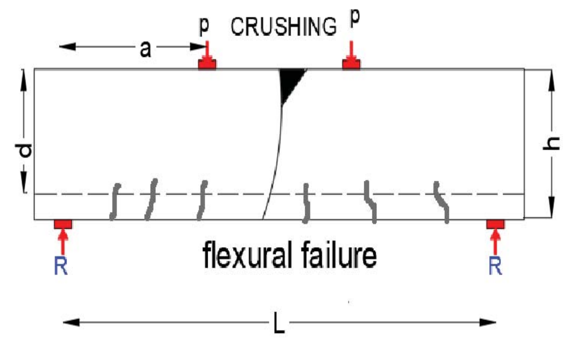


Figure (1-2): Flexural failure of deep beam (Kumar, et al., 2019)

2. **Flexural-shear failure:** Failure due to flexural-shear occurs when there is sufficient tension reinforcement and flexural cracks are leading the advancement of inclined diagonal cracks in the maximum moment zone. As demonstrated in Figure (1-3), failure-causing cracks will propagate upward from the zone of support to the zone of load.

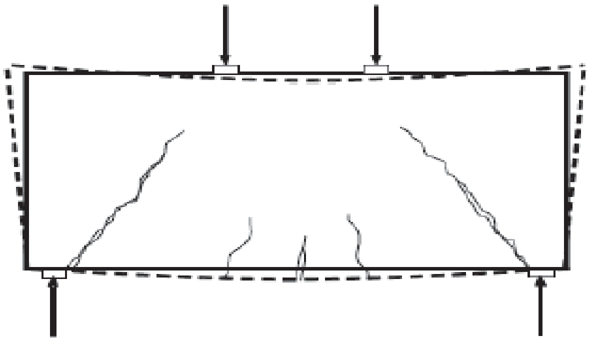


Figure (1-3): Flexural- shear failure of deep beam (Kumar, et al., 2019)

3. **Diagonal splitting failure:** Diagonal splitting failure occurs as depicted in Figure (1-4), when the final diagonal crack spreads

between the support and the load, propagates outwards from the midspan.

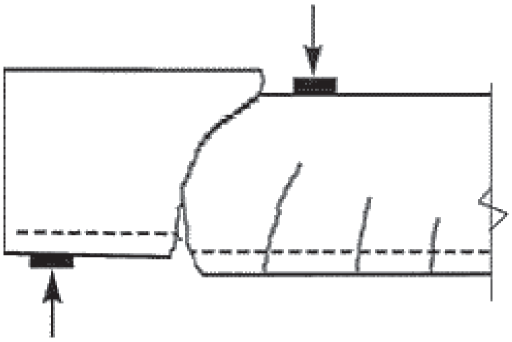


Figure (1-4): Diagonal splitting failure of deep beam (Nghiep, 2011)

4. **Diagonal compression failure:** The line between the support with the load first experiences the development of an angled crack. Another parallel inclined crack appears after an additional load increase, this one developing closer to the supporting point than the first inclined crack and rising as the load increases. The destruction of the concrete between the first and second cracks, which functions as a strut between the support and the load points, Figure (1-5).

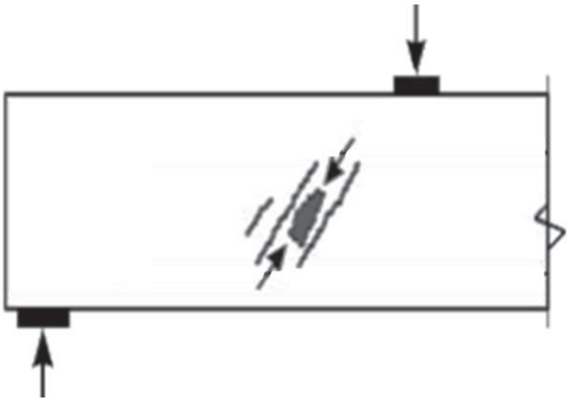
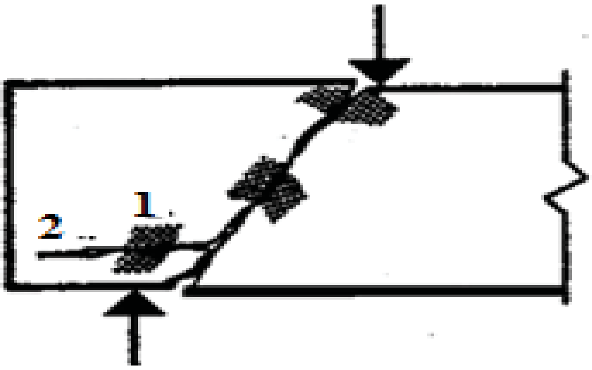


Figure (1-5): Diagonal compression failure of deep beam (Sharma, 2014)

5. **Bearing failure:** This failure happens as a result of an increase in high strains in the loaded sections or above the support portions; crack No. 1 in Figure (1-6).

6. **Bond failure (Anchorage failure):** High flexural bond stresses can combine with high local bond stresses at the extremities of the beams, as demonstrated by crack No. 2 in Figure (1-6). The longitudinal reinforcement may be secured by a plate or by the embedment of straight bars, hooked bars, or headed bars ACI 318M-19, R23.2.6 in order to prevent bond failures. According to ACI 318M-19, 25.3.1, a standard hook is one that has a 90-degree bend and an extension that is 12 times the diameter of the bar behind the bend. The point when the bars are fully grown is where the hook must be placed. According to the Strut and Tie Model (STM), each support's compression-compression-tension (CCT) vertical face is where the longitudinal tension reinforcement of the tie can fully develop. They occur when the primary stress of tension in the member web exceeds the tensile strength of the concrete. Web-shear cracks appear as splitting or bursting cracks in deep beams. Web-shear cracks typically develop as a result of transverse tensile stresses brought on by the distribution of compressive loads in the bottle-shaped struts. It is clear that the width of flexure-shear cracks is also influenced by the spreading of compressive loads in deep beams.

It is important to note that the main factors influencing the flexural crack width are the steel stress, bar spacing, and concrete cover (Nawy, 1991). Transverse reinforcement, a/d ratio, longitudinal reinforcement, and concrete cover are additional important factors that affect the diagonal crack width (Birrcher et al., 2009).



1-Bending failure

2- Anchiorage failure

Figure (1-6): Bearing and Anchorage failures in deep beam

1.2.2 Crack Types in RC Deep Beams

RC deep beam crack types are depicted in Figure (1-7). Flexural cracks spread from the soffit of the deep beam. Web-shear cracks and flexure-shear cracks are two more forms of shear cracks that are known to occur in RC deep beams (MacGregor and Wight, 2005). After or combined with the production of flexural cracks, flexure-shear cracks are also obvious. Flexure-shear cracks grow from the flexural crack's termination to the load source.

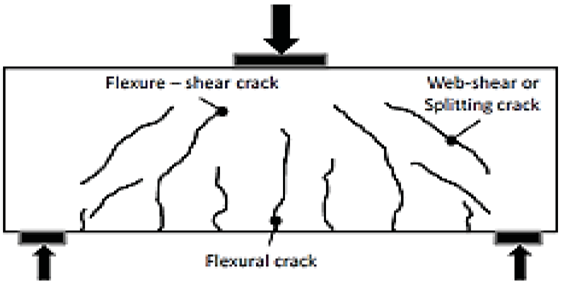


Figure (1-7): Types of cracks in reinforced concrete deep beams (MacGregor and Wight, 2005)

1.3 Modeling with Struts and Ties

The St. Venant principle states that at distances greater than or equal to the height (h) from the point of loading, the strains brought on by a discontinuity in the load or a change in the properties of the section are nonlinear. When the load discontinues or a dimension change at a point closer than the distance h, Saint Venant's principle does not apply. As a result, the reinforced concrete members close to concentrated loads, holes, and dimension changes develop discontinuation zones. In such a scenario, concrete members can be split into two zones: the first, known as B regions (Bernoulli), in which Bernoulli's theory is applicable, and the zones in which interruptions alter the behavior of the concrete members (D regions).

It is possible to use the theory of elasticity to calculate the stresses within B regions at low compressive stresses when the concrete is elastic, i.e., not cracked. However, when the concrete cracks, this stress field will be disturbed, causing a redistribution of internal forces. When this happens, the strut-and-tie model (STM) can be used to depict the internal forces in a truss-like manner. For reinforced concrete structures and prestressed concrete structures, strut and tie modeling is a method of analysis that reduces complicated states of stress in a structure to a collection of simple stress paths. The recommended truss members experience uniaxial stresses due to the stress routes. In compression, truss members are referred to as struts, while in tension, force lines are referred to as ties. As seen in Figure (1-8), nodes are the places where ties and struts join together. A truss mechanism is made up of ties, struts, and nodes. (Brown and Bayrak, 2006).

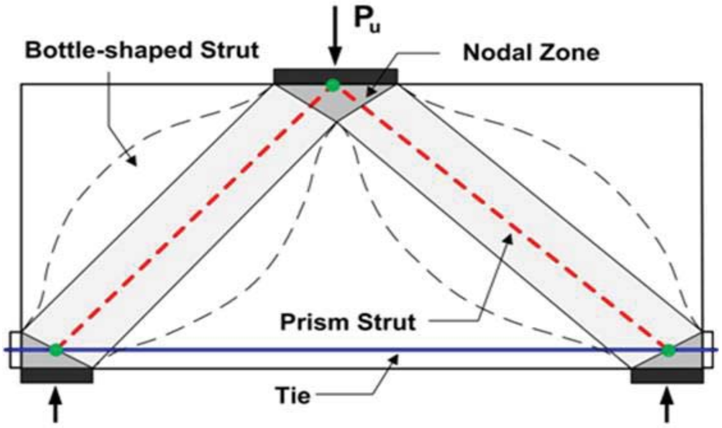
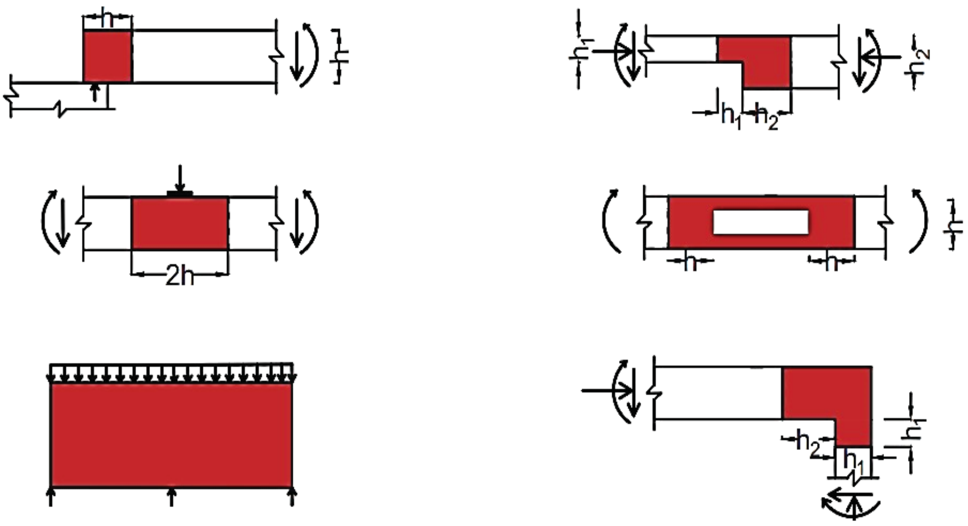


Figure (1-8): Truss-like assumption of Strut and Tie modelling, (Brown and Bayrak, 2006)

Node equilibrium and overall equilibrium are taken into account during the analysis stage. To establish the yield requirements for ties, struts, and nodes, empirical observation of these components is used to ascertain their constitutive relevance. The lowest bound of plasticity theory, which states that only yield conditions and equilibrium must be persuaded, is therefore followed by strut and tie models (Brown and Bayrak, 2006). The lower bound of plasticity theory states that a load will not cause a body to collapse if it is sufficient to allow the finding of a stress distribution that is identical to stresses at the yield surface while maintaining external and internal equilibrium (Nielsen, et al., 1978). More particular, a lower bound technique guarantees that a structure's capacity will be at most equal to or lower than the actual collapse load.

1.3.1 Discontinuities in Reinforced Concrete Members' Regions

The strain distributions of structural members that have a change in the geometry of element in a structure or in a reaction or concentrated load as shown in Figure (1-9) can typically be split into two Band D regions, where they are nonlinear. The strut and tie model has recently been recognized as a useful technique for designing both B and D regions. St. Venant’s principle states that bending and axial load-related stresses are distributed linearly at a distance from the discontinuity about equal to member height. According to the ACI 318M-19 Code, discontinuities are defined for this cause as extending h distances from the section where the change in geometry or load is present.



Loading discontinuities Geometric discontinuities

Figure (1-9): Typical D regions, (ACI 318-19, Chapter 23)

Thus, the following regions can be assigned to a structural element:

- ***B Regions:*** They are the components of a member that can be employed to deal with the "plane section" underlying assumptions of the standard beam theory.
- ***D Regions:*** All of the regions outside of the B zones where cross-sectional planes do not remain laid out after loading belong in this group. D areas are frequently presumed (ACI 318M-19) when there are discontinuities or disruptions in the distribution of stress at certain locations on a structure member.

1.3.2 Elements of Strut and Tie Model

1.3.2.1 Struts

Compression parts in an STM are called struts. They stand for concrete stress fields with primary compressive stresses primarily along the strut's centerline. A strut in a planar (2-D) member's idealized concrete stress field might have a prismatic, bottle-shaped, or fan shape. The geometry of a strut is determined by the applied load type. According to (**Nielsen et al. 1978**), there are three types of struts:

- **Prismatic Strut*:*** the most fundamental type of struts. As seen in Figure (1-10 a), a prismatic strut has a constant cross-section along its entire length. Such a strut can exist in a beam when the neutral axis limits the compressive stresses. According to Brown and Bayrak (2006).
- **Bottle-Shaped Strut:** Because the flow of compressive loads is not limited to one area of a structural element, as shown in Figure (1-10 b), a bottle-shaped strut can arise. In this instance, a tiny area is subjected to the load, and the stresses are distributed as they pass through the member. As it divides, the compressive stress reverses course and creates an angle with the strut's axis. In order to maintain balance, a tensile force is created to oppose the lateral component of the angled compression forces.
- **Compression Fan Strut:** It is specialized due to the fact that it focuses care on such a small zone. Stresses cause a radial flow from a large to a smaller zone. When large uniform loads flow into a support, a compression fan is formed, as shown in Figure (1-10c). Because the forces are collinear and there are no tension components perpendicular to the fan zone, the developed tensile stresses have no value (Brown and Bayrak, 2006).

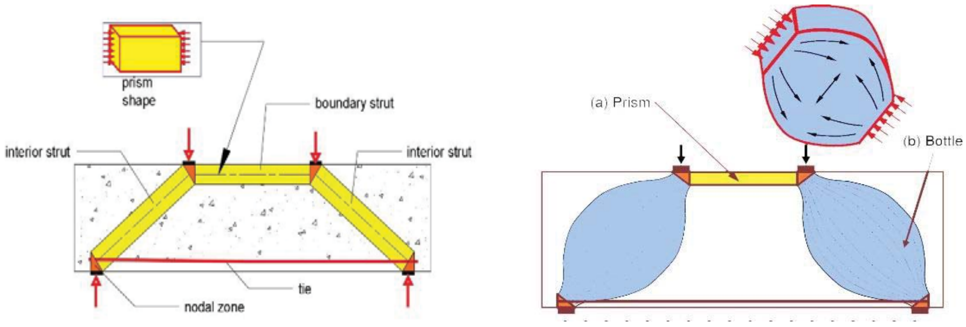


Figure (1-10a): Prism Strut type **Figure (1-10b):** Bottle Strut type

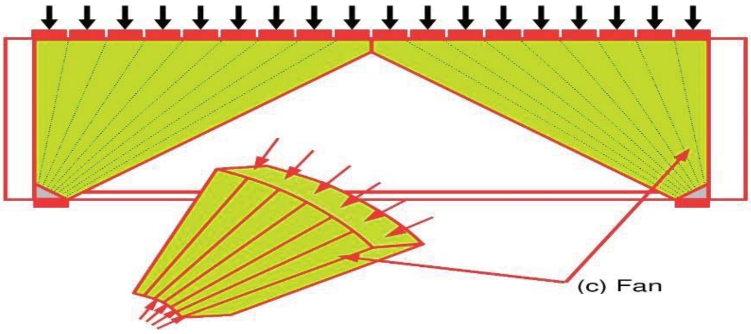


Figure (1-10c): Fan Strut type

Figure (1-10): Strut type

1.3.2.2 Ties

The components that carry tension are called ties, and they are mainly used as reinforce bars. As a result, a tie's geometry is much simpler than that of a strut or node. The permissible force is mostly determined from the yield force, and the tie is geometrically restricted to parts that can support high tensile forces.

Ties consist of a section of the enclosure concrete that is concentric with the tie axis, deformed rebar, prestressing rebar, or both. The enclosure concrete is hard ever thought to be able to bear axial force in the model. When reducing the tie's elongation, it also stiffens the tension, which is particularly helpful when resisting loads. It also describes the region in which the forces of the ties and struts are to be anchored.

1.3.2.3 Nodes

Nodes, which represent the joints in a strut and tie model, are the sites where the axes of the struts, concentrated loads, and ties meet (ACI 318M-19). Another method to define a node is the point in a strut and tie model where forces are diverted. A particular node of the model should be subjected to at least three forces in order to maintain equilibrium. The following list of nodes is based on the sign of the forces working on them (Fu, 2001):

- C-C-C: is the node that resists three compressive forces.
- C-C-T: is the node that resists one tensile force and two compressive forces.
- C-T-T: is the node that resists two tensile forces and one compressive force.
- T-T-T: is the node that resists three tensile forces.
- T-T-C-C-C: is the node that resists two tensile forces and three compressive forces.

The nodal zone, shown in Figures (1-11a) and (1-11b) is the zone of concrete that is thought to convey strut and tie forces through the node. Hydrostatic nodal zones, which were recently replaced by expanded nodal zones, were employed in the early strut and tie models. The hydrostatic phrase describes how stresses in the plane are uniformly distributed in all directions.

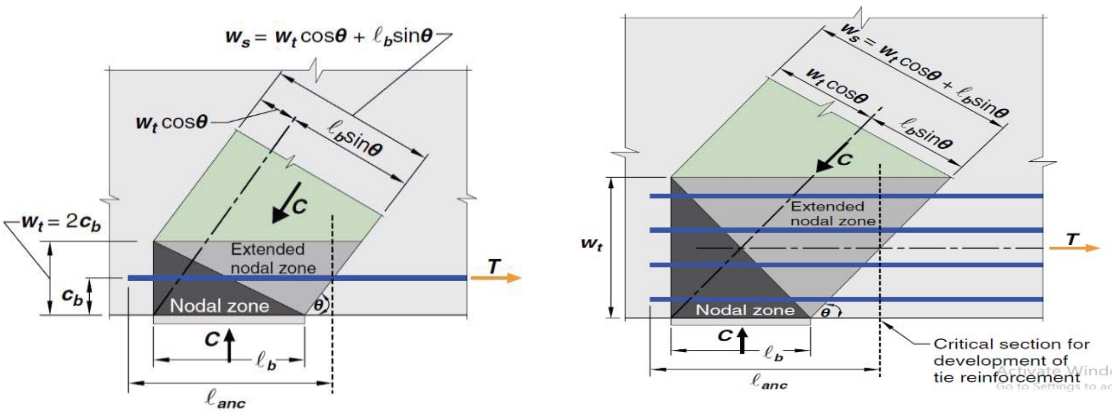


Figure (1-11a): One layer of reinforcement

Figure (1-11a): Distributed reinforcement

Figure (1-11): Nodal and extended nodal zones, (ACI 318M-19)

1.4 Reinforcement limitations

1.4.1 Secondary Reinforcement Limitations

ACI 318-19, 9.9.3.1 states that the secondary reinforcement distribution along with the side faces of deep beams must at least meet the requirements in (a) and (b):

(a) The "distributed reinforcement area normal to the longitudinal beam axis, **A_v**, shall be at least **$0.0025b_ws$**, provided that the spacing of the distributed transverse reinforcement is **s**".

(b) The "distributed reinforcement area parallel to the longitudinal axis of the beam, **A_{vh}**, shall be at least **$0.0025b_ws_2$**, where **s_2** is the spacing of the longitudinal reinforcement distribution". The spacing of the necessary distributed reinforcement shall not exceed less than 30 mm and d/5 (ACI 318-19, 9.9.4.3).

1.4.2 Main Reinforcement Limitations

The minimum flexural tension reinforcement area, **$A_{s,min}$**, is the larger of (a) and (b), for a statically determinate beam (ACI 318-19, 9.9.3.2):

(a) $\frac{0.25\sqrt{f'c}}{F_y} b_w d$ ------------ (1-9)

(b) $\frac{1.4}{F_y} b_w d$ ------------ (1-10)

1.4.3 Concrete Cover Limitations

Unless a higher concrete cover for fire protection is provided by the general construction code, the minimum defined concrete cover approach is 75 mm maximum and 10 mm minimum (ACI 318-19M, 20.5.1.1).

1.6 Objectives of the Study

The second objective of the current study is to investigate the efficacy of strut and tie method (STM), depending on the fact that the box girder under study is a deep member. While the first objective of the current study is experimentally investigating the effect of some important parameters on the behavior of reinforced concrete deep box girders. The parameters that are taken into the considerations:

1. Main steel reinforcement,
2. Vertical and horizontal web secondary shear steel reinforcements,
3. Web width of the box girder, and
4. Changing in loading type.
5. Method was also proposed for casting and reinforcing frame box girders with less weight, cost in addition to service opening gain.

1.7 Thesis Layout

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

- **Chapter One** represents a general introduction about RC box girders, deep beam, STM, reinforcement limitations, in addition to the study objectives.

- **Chapter Two** represents a review of some previous research works with theoretical, numerical and experimental investigations that are achieved on reinforced concrete box girders, deep beams, and STM validation.
- **Chapter Three** deals with the properties of the utilized construction materials in addition to the experimental work plan.
- **Chapter Four** deals with presenting test results of the laboratory 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.

Behavior of Reinforced Concrete Deep Box Girders

Rawaa Najm Abood

Supervisor:

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ABSTRACT

One of the things that really deserves to be studied is the box-girder when it is deep. Where it is noticed that such a structural member has recently begun to spread due to the boldness in increasing the sizes of this type of members. Accordingly, sixteen deep box girder specimens of reinforced concrete cast were experimentally tested in order to study the behaviour and load capacity of the deep box girder in addition to trying to suggest a different reinforcement for it. A number of important affective parameters were dealt with, such as the roles of web horizontal, web vertical, and main reinforcement, the width of the web, not to mention the load type. The concrete was omitted and the conventional reinforcement was replaced with a suggested fan reinforcement. It was found that when changing the type of load from one load to two loads and then to a uniform load, the load capacity increased by 24 and 49 % and the deflection decreased by 12 and 20 %, respectively. That takes place according to the fact of the more the load distributed over the span, the lower the stress concentration. On the other hand, the distribution of the load more leads to an increase in the strut-tie angle by 35 and 168 %, which increases the strut strength.

When omitting the vertical web reinforcement, the load capacity and deflection decreased by 18 and 16 %, respectively compared to the reference conventional specimen. The reason for this is due to the absence of vertical web reinforcement affecting the strut strength more than the absence of horizontal one because the strut-tie angle is less than 45 degrees (34 degrees). This is the reason that when the horizontal web is unreinforced, the load capacity decreased by 7 % in comparison to the reference conventional specimen. As for the deflection, it is relatively more in the absence of horizontal reinforcement because the section moment of inertia became less. When both horizontal and vertical web reinforcement were omitted, the load capacity and deflection decreased by 26 and 83 %, respectively because the failure is in the strut region, which was greatly affected by the absence of both web reinforcements.

On the other hand, when both horizontal and vertical web reinforcement were increased from 4 mm to 8 mm in diameter, i.e. by increasing the area of steel by 300 %, it led to an increase in the load capacity and decrease in deflection by about 63 and 50 % for the same reason above.

When reducing the main reinforcing steel by using a diameter of 8 mm instead of 12 mm, the load capacity decreased and deflection increased by 3.3 and 10 %, respectively due to the fact that the elongation in the tie became greater and thus the struts were weakened. In the case of the main reinforcing steel being completely omitted, the deep members STM (strut and tie method) truss was not formed, which led to a rapid failure, so that the load capacity and deflection decreased by 71 and 54 %, respectively compared to the conventional reference specimen. It is worth noting that the horizontal web steel, in addition to the low tensile strength of the concrete, contributed to the low strength when the tie steel was completely absent.

When the width of the web was increased from 65 mm to 100 mm, i.e. an increase of 54 %, the load capacity increased by about 64 % due to the increase in the strut strength by increasing the concrete section, while the deflection decreased by about 1.2 % for the same reason. In the case of a distributed load, a fan strut is formed so that the middle part of the box girder remains almost stress-free.

Accordingly, in this study, frame forms were cast with a middle part omitting, while the remaining concrete part was reinforced with fan reinforcement only besides the traditional reinforcement of the tie. These frames were subjected to three types of loading: one centre load, two centre loads, and the aforementioned disturbed load. The proposed reinforced frame showed less load capacity than their conventional counterparts by about 21, 23 and 3 %, respectively, but they maintained their superiority over the theoretical STM, ACI 318-19 method by about 54, 29 and 21 %, respectively. That made the proposed frame a good alternative, especially since it less weight and provides openings for services by about 20%, each.