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Effect of Torsion on Different Types of RC Beams: A Review

Zainab F.Yawer, Dhuha A. Mohammed Baqer, Safa A. hussien, and Anmar H. Salih

[1] Mustansiriyah University, Department of Construction and Project Management, Baghdad, Iraq
[1]E-mail of First Author : zainbfaiq@uomustansiriyah.edu.iq
[2]E-mail of Second Author : Dhuhaadnan@uomustansiriyah.edu.iq
[3]E-mail of Third Author : Safa_zada@uomustansiriyah.edu.iq
[4]E-mail of Third Author : mranmarukra@uomustansiriyah.edu.iq

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ABSTRACT

This research reviews some sources that discuss the application of torsion on reinforced concrete beams, whether these beams are square or rectangular (solid or hollow) or box beams and T-beams. Torsion can affect reinforced concrete in buildings, including curved girders in bridges, balcony girders, and spiral stairways, potentially leading to their direct failure, which is extremely dangerous. Therefore, research is focused on studying such types of forces to reduce their impact on buildings and provide greater durability during the operational period of the buildings. The behavior of torsion on the reinforcement in concrete components and the influence of the moment in designs have also been mentioned, along with some previous research by a researcher that discusses the effect of the torsion. In the final part of this research, the equations used by the researchers are mentioned, as well as a comparison between previous studies and the equations of the code that was used in this research.

1. Introduction

Significant torsional moment is applied to many bridge and building structures, which influences structural design and may call for strengthening. It's possible that reinforced concrete members require strengthening because they don't have the torsional shear capacity. There are a number of reasons, such as insufficient transverse steel brought on by mistakes in construction and a decrease in the effective rebar area as a result of corrosion or elevated loading owing to a shift in utilization. Furthermore, current design codes have lower overall safety factors than in the past. Thus, torsion is becoming a prevalent issue. When exposed to increasing torsion, reinforced concrete members may fail very quickly [1]. Areas that experience abrupt failure due to seismic activity are more likely to experience torsional failure. Unwanted loading causes brittle failure, or torsional failure [2]. Participants in a structural system might experience torsion due to either primary or secondary actions. When torsion is required to resist an external load, this is known as primary torsion. The torsion necessary to preserve static equilibrium in such circumstances can be identified in a unique way. Another name for this situation is equilibrium torsion. Examples of primary or equilibrium torsion include cantilevers, eccentrically loaded girders, and an eccentric line load applied along the span of a simple member. Torsion, also known as secondary torsion, can arise from the requirements of continuity in structures with static indeterminacy. Serious damage could be the outcome of statistically indeterminate reinforced concrete RC structures' disregard for continuity in different loading steps [3]. The

Corresponding author E-mail address: zainbfaiq@uomustansiriyah.edu.iq

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bridge girder's bending torsional deformation and transversal torsional deflection brought on by lateral wind force or transversal seismic action may have a significant impact on designs of large bridge structures. Because of this, a lot of investigators have focused a lot on the effects of lateral inclination coupling of bending torque on torsional capacity and stability damage [4]. When designing a safe structural member, shear forces, axial forces, torsion, and bending, or a combination of these four effects, are taken into account [5]. An essential design tool is the idea of a plastic hinge with torsion areas where the reinforcement bars give way. It is more challenging to achieve ductile behavior in thin beams with pure torsion compared to simple beams. Because specimens are thin, when the outer fibers of the cross section reach their higher strength, there is no concrete inside to absorb stresses. The exterior diameter of the ring decreases when the outer fibers break, and the presence of a concrete nucleon becomes increasingly important for the beam's performance [6]. To stop compressive concrete structures from failing prior to the reinforcement in torsion-prone reinforced concrete members yielding, the greatest torsional reinforcement amount is specified. Large-scale concrete structures made of intricate and thin participants have been built thanks to developments in structural design technologies and building materials [7]. Using experimental, finite element, and theoretical analysis techniques, some researchers have conducted pertinent research on CFST members' torsional mechanical performance [8]. In the field of bridge engineering, composite box girders with webs made of corrugated steel (CBGCSWs) have emerged as appealing constructions. However, due to the significant reduction in torsional stiffness brought on by the thin webs of corrugated steel (CSWs), (SBMC-CBGCSWs) wide single-box multi-cell CBGCSWs (SBMC-CBGCSWs) may experience abrupt failures under high eccentric loads [9].

2. Previous Studies about Torsion on Different Types of RC Beams

Soluit, A. K, et al, 2007 [10] Seventeen beams in all were put to the test. According to experimental results, the ability to resist torsion of the tested RC beams can be significantly expanded by using externally bonded FRP sheets. The final moment of torsion of GFRP- and CFRP-strengthened beams increased by 132% and 163%, respectively, relative to the control beam. **Abdul-Hussein, 2010 [11]** The beams that were tested have a side length of 150 mm and a square cross-section of 1020 mm. Beam form (both hollow and solid sections). Various fiber fraction volumes (0, 0.5, 0.75, and 1 percent) have been employed, along with varying amounts of longitudinal and transverse steel ratios. It was found that adding 1% steel fibers to the concrete mix significantly raised the ultimate and cracking torques. Solid and thin sections of the (ultimate and cracking) torque have elevated about 43% and 66% for solid and 57.7% and 53.2% for hollow, respectively. **Ragab, K. S, and Eisa, A. S, 2013 [12]** Seven beams in all, divided into three groups, underwent testing. All beams are 2000 mm long and have a cross-section of 100 x 200 mm. The behavior of torsion on reinforced beams with GFRP bars was found to be extremely similar to that of concrete beams reinforced with regular steel. In comparison to reinforced beams with regular steel, the ultimate torsion moment is halved when GFRP bars are used as reinforcement. **Ahmed, A. S, et al, 2015 [13]** All four tested samples had the similar measurements: length (1500 mm), height (200 mm), and width (100 mm). The distance between shear connectors was the primary variable measured during the test program. Depending on the distance between the shear connectors, rectangular reinforced concrete beams reinforced with a steel plate's cracking load beneath pure torsion can increase from 150% to 250%. Depending on the distance between the shear connectors, the ultimate load of reinforced rectangular concrete beams strengthened with a steel sheet beneath pure torsion can range from 178% to 278%. **Al-Hassani, H. M, et al, 2015 [14]** Ten RPC T-beams with various section types (solid and hollow), measuring dimensions, length (1300 mm), web width (100 mm), and height (160 mm), were put through a pure torsion test. Raising the steel fiber content of the concrete mixture from zero to two percent produced increases of 191% and 64% for the solid cross-section and 174% and 59% for the thin cross-section, respectively, while keeping constant longitudinal and transverse reinforcement ratios (p=0.01, p=0.02). This finding suggests the core of concrete has little effect on the final torsional strength and beam elongation. **El-HakimKhalil A, et al, 2015 [15]** Ten similar square box beams made of RC single cells with a 500 mm x 500 mm cross section made up the experimental setup. The loaded span was 2300 mm, but the beam's overall span was 2600 mm. With ratios ranging from 31% to 58%, respectively, the outcomes of the experiment demonstrated that strengthening in both the vertical and horizontal directions significantly increased the box beam's torsional capacity with and without opening. The vertical direction was used to improve the contribution. In comparison to beams without openings, it was found that the torsional capacity was decreased when transverse openings were present. In contrast, the torsional capacity was enhanced by EPT strengthening at the opening. **Abdo, T and Mabrouk, R, 2017 [16]** Every beam has a fixed cross-section width (150 × 300 mm) and a constant clear span length (1800 mm). The greatest torque for the beam with one opening was 26% less in relation to the initial beam, and the greatest torque for the beam with two openings was 34% lower. In contrast, there was a 35% and 42% decrease in cracking torque. Structural engineers may deepen a beam with openings and/or reduce the distance between stirrups surrounding the opening to increase the beam's torsional capacity. **Atea, R. S, 2017 [17]** For this purpose, twelve T-beams with simple supports were tested. The concrete specimens that were used had flange dimensions of 450 mm x 55 mm x 1300 mm, a web of 90 mm x 180 mm x 1300 mm, and end components of 450 mm x 235 mm x 250 mm. The results showed that adding strengthening to the flange resulted in the same percentage rise as when the web is strengthened without anchoring. The T-beam's energy absorption and ductility capacity improve significantly when it is strengthened with additional longitudinal CFRP strips. The T-beam's twist capacity was increased by using longitudinal CFRP strips with (90º) or (45º) CFRP. Concrete splitting between the web and flange was the cause of the failure. The presence of 90º or 45º CFRP in the web and flange without anchoring reduces the energy absorption and ductility capacity of T-beam in when contrast to the source beam. **Alamli, A. S, et al, 2017 [18]** Ten reinforced concrete T-section beams composed of square and circular web perforations in Reactive Powder Concrete (RPC) were tested in pure torsion. The T-section beam utilized in this investigation has the following measurements: bw=100 mm, h=280 mm, bf=320 mm, tf=80 mm, with a length of 1300 mm. In this study, web openings included many variables (shape, dimension, location, and number), which are listed below. It was found The distribution of shear stress is not uniform throughout the web due to opening eccentricity, resulting in a reduced torque capacity. The final torque reduces as the opening grows. **Kandekar, S. and Talikoti, R. 2018 [19]** The experimental investigation involved casting 21 reinforced concrete rectangular beams. The beam dimensions were measured at the cross-section (150 mm × 300 mm) and length (1300 mm). The highest moment load of beams is raised by strengthening with 100 mm spacing by 140% compared to controlled beams and is 11% smaller than torsionally designed beams. The highest moment load of beams rises by 100% for a 200 mm spacing when contrasted to the regulated beam. It has been observed that all beams wrapped with aramid fiber strips have a higher carrying capacity of torsional moments. When the distance between the strips grows, the torsional moment carrying capacity decreases with small changes in the angle of twist. **Abdullah M. D, 2018 [20]** This study used six different amounts of volume of fibers (0%, 0.5%, 0.75%, 1.75%, 2%, and 2.5%) to find out the impact of volume of fibers on the RC beams' torsional strength. Twelve squaresectioned, hollow and solid reinforced concrete beams measuring 160 mm in height and 1000 mm in length were tested beneath pure torsion. When the steel fiber percentage was raised from zero to 2.5%, ultimate and crack torsional capacity in the solid section increased by 98.2% and 178%, respectively, while in the hollow section they increased by 91.3% and 163%. The core of concrete had ultimate torsional strength and was unaffected by elongation of the beam, according to the experimental outcomes.

Hadhood, A, et al, 2020 [21] Six reinforced beams with GFRP bars were designed with a cross-section of 200×400 mm and a length of 3000 mm. All beams failed beneath tension owing to GFRP transverse reinforcement rupture at curved parts (ρ_T ranged from 0.36% to 0.89%). Utilizing GFRP spirals as transverse torsional reinforcement for beams with 36 MPa, the durability of concrete may be considered underneath reinforcement; additionally, in terms of post-cracking stiffness and final torque, the rectangular-spiraled GFRP beam (spirals in the settling path of the supplied torque) performed better than its stirrup counterpart. This specimen had a lower angle of twist. **Kim, M. J, et al, 2020 [22]** Eleven experiments were carried out to observe the behavior of pure torsion for RC members with respect to the characteristics of their cross-section. The experimental outcomes showed the quantity of transverse torsional reinforcement raised the torsional stiffness and strength of the RC beam specimens, whatever the cross-section properties. In contrast to specimens with solid cross-sections, thin beams with cross-sections showed greater torsional stiffness and high torsional strength after the initial torsional crack. **Ayoub H. M, 2020 [23]** Thirteen RC box beam specimens with identical dimensions (1800x300x300 mm) were cast and put through experimental testing beneath pure torsion. The ultimate torque capacity was increased by approximately 20%, 21.15%, 24%, 25.7%, and 57.14% for NOST-strengthened beam specimens utilizing localized steel plates with a single face, one opened steel diaphragm, two-face localized steel plates, CFRP strips, and two opened steel diaphragms. **Muhammed, S. H, and Aziz, A. H 2020 [24]** The span length, width, and height of four specimens are 2100 x 300 x 300 mm, with a cover thickness of 60 mm. These FSSRs were designed as bolts as shear connectors to be completely bonded with SCC. According to the test results, one, three, and five FSSR-strengthened specimens have an ultimate torsional capacity that is 45.7%, 75.5%, and 122.4% higher than the reference specimen. **Lee, J. Y, et al, 2021 [25]** beams had a cross-section of 400 × 600 mm with a length of 2500 mm. However, when the yield reinforcement strength exceeded 420 MPa, 18% of the 153 specimens failed due to torsional compression. The strength ratios of shear (V_{test}=VACI-19) and torsion (T_{test}=TACI-19) decreased as both the quantity and yield strength of reinforcement rose. The T_{test}=TACI-19 value for torsional parts meeting the same code restrictions was found to be 1.13, which is significantly less than that of shear specimens. V_{test}=VACI-19 was greater than 1 in order; more than 95% of shear specimens made of steel with high strength failed with the ST Failure status. **Mahdi M. S, and Mohaisen S. K, 2021 [26]** Six deep beam samples have dimensions of 1300 mm in length, 115 mm in height, and 400 mm in width and were tested beneath the impact of pure torsion. Self-compacting concrete (SCC) was one of these samples, with steel fibers (SF) added in two ratios (0.75% and 1.5%). It was discovered that adding 1.5% steel fiber to the SCC mixture improved the samples' behavior more than other steel fiber ratios. **Abdullah, M. D, and Abodi, J. T, 2022 [27]** Twenty-six beams made of reinforced concrete measuring 250, 250, and 1150 mm wide, high, and long, respectively, were tested beneath pure torsion. Examine how the longitudinal reinforcement ratio, steel fiber ratio, and stirrup ratio affect highly resistant concrete. The outcomes show that as the steel fiber ratio increases, the concrete's behavior changes from brittle to ductile, with the highest torsional ductility index (3.98). Raising the amount of steel fiber to 6% led to a 105% rise in torque, but it was only a slight rise in torque when compared to the 2% steel-fiber amount. **Ibrahim A, et al, 2022 [28]** Ten RC specimens underwent experimental testing. Two beams had solid cross sections, while eight had hollow sections. The specimens measured total depth (400 mm), total length (2400 mm), length (1600 mm), and cross-section (300 × 400 mm). The findings demonstrated that torsional capacity was increased by roughly 16% and 18%, respectively, when inclined spiral rectangular stirrups were used to reinforce RC solid and hollow beams, as opposed to employing traditional closed stirrups. **Said, M, et al, 2023 [29]** Thirteen of the RC beams were tested for pure torsion and loaded to failure with a cross-section of (150 × 300) mm and a length of (2000) mm. The results show using hybrid fibers enhanced the torsional behavior of RC beams. As a result, the higher torsional strength rose by 22.3% for (0.75% BF and 0.75% CF), 28.6% for (0.75% BF and 0.75% SF), and 65.2% when (0.75% CF and 0.75% SF) were merged. **Ahmed S. T, 2023 [30]** The specimens consist of ten reinforced rectangular beams subjected to pure torsion with identical dimensions (1200x200x150 mm) in length, width, and height, respectively. The specimens had two variables: the percentage of steel slag incorporated into the mixture, which was 5%, 10%, and 10% & 30% of the cement in the first, second, and third categories, respectively. The other variable is the type of specimen, which can be solid or hollow. When hollow and solid specimens with the same percentage of steel slag incorporation were compared, the results showed that only the control specimens provided the same ultimate torsional capacity, albeit the cracking torsional capacity for the hollow specimens was lower all across the board, and the higher torsional capacity for all other specimens was lower when hollowed. The groups' final torsional capacity reduction percentages were as follows: 6% for the group that replaced the cement with 5%, 16% for the group that added 10%, 11% for the specimens that replaced 10% of the sand, and 10% for the specimens that replaced 30% of the sand.

3. Torsional Behavior of Concrete Members

One of the fundamental structural actions that is not given much attention but is crucial for assessing structures that are subjected to wind and seismic loads is torsion. When examining structures that are subjected to lateral forces, torsional rigidity, toughness, and twists at maximum torque are crucial factors [31]. For the engineering environment, interest in building durability is a constant concern [32]. Torsional failure in structures is one of the riskier kinds of failure because it occurs suddenly and doesn't give any warning of an impending failure [33]. When an element is subjected to a load that is not at the cross-sectional center, it twists, a phenomenon known as torsion. Newtons and meters are examples of units of length that are used to express force [34]. Up until the concrete beam cracks, torsional strength is the total strength of concrete and steel reinforcement. After that, longitudinal bars and stirrups provide the majority of torsional strength, and outside concrete cover stirrups are comparatively ineffective [35]. Unwanted and dangerous, abrupt brittle failure is the nature of failure in torsion members with insufficient reinforcement. This emphasizes even more how crucial torsion design is for concrete members because, if not adequately reinforced, a torsion failure does not provide an indication. Concrete members subjected to twisting moments that require precise torsion include spiral staircases, balcony girders, and curved girders in bridges. Figures (1) illustrate structures exposed to torsion. As depicted in Figure (2), the angle of cracking inclination (θ) is determined by the force applied to stirrups divided by the force applied to longitudinal reinforcement [36].

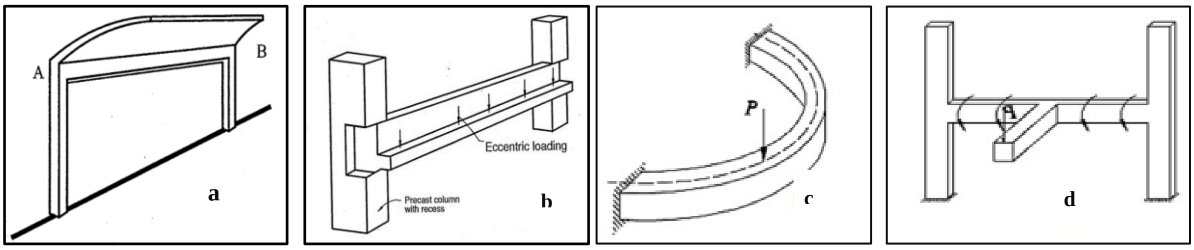

Figure 1. Structures Torsion-Susceptible (a) and (b) [36] (c) and (d) [37]

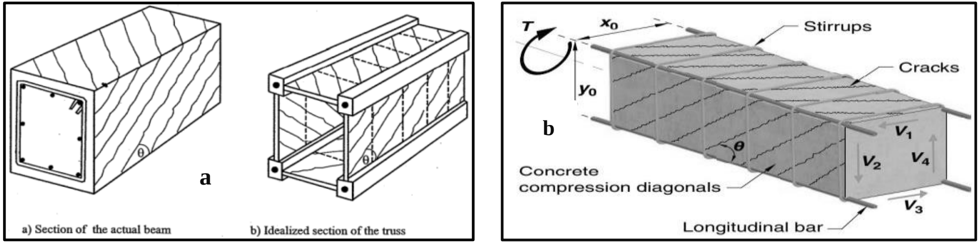

Figure 1. (a) Idealized Torsion Cross Section [36]. (b) An Analogy of Space Trusses Illustrating the Angle of Shear Stresses and Cracks [35]

Al-Khafaji, J, et al, 2016 [38] Beams tested under pure torsion are investigated as part of the experimental work. Eleven simply supported reinforced concrete beams measuring a square cross section (150 mm by 150 mm) and 1185 mm in total length were used for the tests. When compared to normal-strength self-compacting concrete, it had been discovered that using high-strength self-compacting beams considerably raised the maximum and cracking torques of the tested beams. **Jabbar, S, et al, 2016 [39]** Using ABAQUS programs, five hollow beams measuring cross-section size (600 x 600 mm) and length (5900 mm) were used in the study. Under pure torsion, the torque load indicated that the thin beam's (H) strength was higher than beam H100 by approximately 1.8% for the HSC beam and 12% for the UHPC beam. The final strengths in beams H200 and H300 were reduced roughly 32% to 82% for the HSC beam and 35% to 75% for the UHPC beam, respectively, compared to the hollow beam (H). **Khuzaie, H. M and Atea, R. S, 2019 [40]** Simply supported T-beams were tested for this purpose. The measured dimensions of all tested specimens were length (1400 mm), web (100 mm), flange (220 mm), and height (160 mm). The RPC thin (T-beam's) maximum torque and cracking were discovered to increase when 2% steel fibers were added to the concrete mix. With all other properties held constant, a 66% increase in ultimate torque and a 184% rise in cracking torque were obtained for hollow sections. **Haroon, M., et al, 2021 [41]** 159 RC beams from the literature are included in an experimental database that was used to train and validate ANN model. The outcomes were contrasted with design codes' predictions. The outcomes show that ANNs are capable of accurately simulating torsional behavior of RC beams. When the variables related to concrete size were changed, there was no discernible shift in the torsional strength of RC beams. Additionally, there was an advantageous correlation between the compressive strength of concrete and its torsional strength, which peaked at about 90 MPa. **Majed, M. M, et al, 2021 [42]** Six medium-sized specimens measuring a rectangular cross-section (350 × 500), length 2500 mm were tested. Growing the number of ongoing FRP laminates encircling the rectangular beams' cross section along their whole length resulted in a notable rise in the final torsional strength (between 36% and 55% in comparison to the control beam), according to the parametric study. For torsional upgrading, it has been discovered that full covering with continuous sheets was significantly more successful. **Mohammed, T. J, et al, 2023 [43]** The results for experimental torsional load and numerical analysis produced by the software of ANSYS agree fairly well. Four RC beams measuring length 1600 mm, and the cross-section (250 x 250) mm made up the finite element analysis. Stirrup configurations were found to be crucial in limiting the kinds of failure mechanisms that may arise in beams subjected to torsion. In general, this paper contributes to the existing literature by demonstrating that using helical stirrups like the transverse reinforcement results in the best torsional behavior of beams.

4. Torsional Moments Considered in Design

Asymmetrical loading, member geometry, and structural framing can all result in the formation of a torsional moment in structural concrete members. For example, the negative bending moment that holds the spandrel beams at the floor slab's exterior end in place results in a torsional moment. Torsional stresses start to form in a beam section when a moment is applied parallel to its surface. These moments, also referred to as torsional moments, cause the structural part to rotate and its surface to crack, typically in the shape of a spiral. Instead of only applying pure torsion moments to structural elements, shearing forces and bending moments are typically applied simultaneously [37]. Both static and dynamic twisting moments are possible, short-term or long-term, cyclical or non-repeated, depending on the type of utilized loading, the member's position within the structural system, and the structural form. The torsion phenomenon rarely happens on its own. It almost always occurs in conjunction with other actions like shear and flexure. Therefore, it combines bending and torsion, which is really useful [44]. As shown in table (1), there are two types of torsion, and they occur whether the structure is statically determinate or indeterminate. This type of torsion is shown in Figure (3)

Table 1: Torsion Types [45]

Equilibrium Torsion	Compatibility Torsion
Occurs in structures that are statically determinate, meaning that there is only one way for torsional moments to be transmitted. Statically determinate torsion is another name for it. Rotating members or redistributing internal forces cannot lessen equilibrium torsion.	Occurs in statically indeterminate structures, where rotation and cracking of the concrete structure may result in The torsional moment has been substantially reduced. The structure experiences force redistribution as a result of this cracking and rotation.

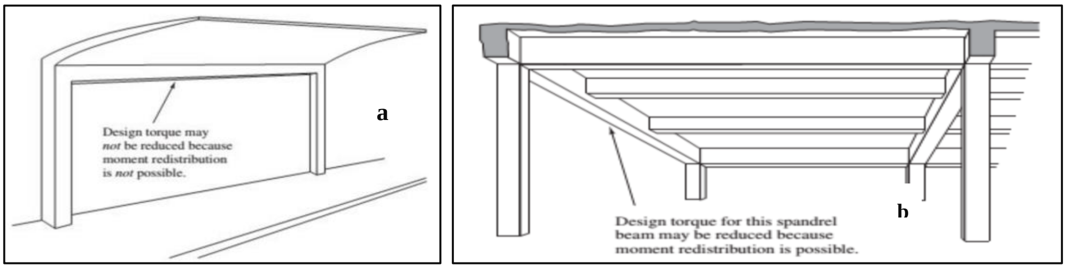

Figure 2. (a) Torsion in Equilibrium (b) Torsion of Compatibility [45]

Sahib. B, et al, 2012 [46] For this study, eight medium-sized reinforced concrete rectangular beams were built. The measuring cross section is 120 x 200 mm, and the length is 1500 mm. It was discovered that the ultimate torque can increase by up to 150 percent when R.C. rectangular beams are reinforced beneath pure torsion using CFRP strips. For pure torsion, the CFRP strengthening will result in higher cracking strength, post-cracking twist, and cracking stiffness than for combined torsion and bending. **Eisa. A and Ragab. K, 2014 [47]** The shapes of beams were selected to produce the bending and torsional moments at the same time. Every beam has (2000) mm long and a cross section (100 × 200) mm. When compared to concrete beams without steel fibers, at a fiber volume fraction of (0.75) percent, torsional capacity of steel fiber self-compacting beams grew about 15.7%. When compared to elevated strength self-compacting concrete beams without steel fibers, the torsional capacities of steel fiber-containing beams raised by 31% at a fiber volume fraction of 1.5%. In contrast, when compared to high strength self-compacting beams without steel fibers, torsional capacities rose by roughly 8% at a fiber volume fraction of 0.75 percent. **Aziz. A, and Hashim. O, 2017 [48]** Six SCC box beam specimens were added and tested; their length, width, and height were 2200 x 220 x 350 mm, respectively. The current study used three variables: the type of diaphragms (opened and closed), the quantity of diaphragms (none, two, and four), and the kind of section (box or solid). According to experimental results, beam specimens with two or four diaphragms for internal strength, respectively, saw an increase in the ultimate torque moment of roughly 58.6% to 72.4% and 120.7% to 127.6%. Additionally, the ultimate torque moment rose by roughly 55.2% to 62.1% when there were four internal diaphragms instead of just two. Additionally, the ultimate torque moment elevated by roughly 48.3% to 55.2% when the section was converted from a solid section to a box section with four internal diaphragms.

5. Equations for Torsion on RC beams

A set of codes and design equations developed by some researchers are utilized in the construction of reinforced concrete beams beneath the application of torsional loads. The following equations have been proposed by researchers and in specific building standards.

Hsu. T and Mo. Y, 1985 [49]

$$T_{cr} = 0.5\sqrt{f'_c}\left(\frac{A_{cp}^2}{P_{cp}}\right) \qquad \dots\dots\dots\dots\dots (1)$$

Koutchoukali. N, and Belarbi. A, 2001 [50]

$$T_{cr} = 0.46\sqrt{f'_c}\left(\frac{A_{cp}^2}{P_{cp}}\right) \qquad \dots\dots\dots\dots\dots (2)$$

Fang. I, and Shiau. J, 2004 [51]

$$T_{cr} = 0.095\sqrt{f'_c}\, X^2 Y \qquad \dots\dots\dots\dots\dots (3)$$

British Standard (EN2004) [52]

$$T_{BS} = \frac{A_{sv} 0.8 X_1 Y_1 (0.87 f_{ys})}{s} \qquad \dots\dots\dots\dots\dots (4)$$

Avinash. S and Parekar. R, 2010 [53]

$$T_u = 0.13 b 2 h \sqrt{f'_c} \qquad \dots\dots\dots\dots\dots (5)$$

ACI 318M-11 [54]

$$T_{cr} = 0.33\lambda\sqrt{f'_c}\left(\frac{A_{cp}^2}{P_{cp}}\right) \qquad \dots\dots\dots\dots\dots (6)$$

Rahal K. N 2013 [55]

$$T_n = 0.33(f'_c)^{0.16} A_c \left(A_l f_{yl} \frac{A_t f_{yt}}{s}\right)^{0.35} \leq 2.5(f'_c)^{0.3} \frac{A_c^2}{p_c} \qquad \dots\dots\dots\dots\dots (7)$$

Prabaghar A, and Kumaran G, 2013 [56]

$$T_{ul} = 2 b_1 d_1 \sqrt{\left[\frac{A_{t\,GFRP}\ f_{y\,GFRP}}{S_v}\right]\left[\frac{A_{GFRP} \times f_{GFRP}}{2(b_1 + d_1}\right]} \times \phi \qquad \dots\dots\dots\dots\dots (8)$$

Makhlouf M. H, 2016 [57]

$$T_u = T_c + T_{Si} \qquad \dots\dots\dots\dots\dots (9)$$

$$T_c = 0.8\sqrt{f_c}\, b^2 h \left(1 - \lambda \frac{d_o}{h}\right) \qquad \dots\dots (10)$$

$$T_{si} = \left[(n A_t f_{yw})_c + (n A_t f_{yw})_s\right] \alpha_t x_t \qquad \dots\dots (11)$$

Zhou J, et al, 2017 [58]

$$T_u = 0.35 f_t w_t + \varphi_1 \varphi_2 A_{cor} \frac{A_u f_{yv}}{s} \cot\theta + 0.015 \frac{A_{cor}}{u_{cor}} b h v_f \frac{l_f}{d_f} \sqrt{f_{cu}} \qquad \dots\dots\dots\dots (12)$$

Amin A, and Bentz E. C, 2018 [59]

$$T = 2A_o \times \min\left[\left(\frac{A_{sv} f_{sv}}{s} + k_{fd} t_c f_w\right)\cot\theta_v \left(\frac{\sum A_{sl,i} f_{sy,i}}{p} + k_{fd} t_c f_w\right)\tan\theta_v\right] \leq 0.25 f_{cm} \frac{1.7 A_g^2}{p} \qquad \dots (13)$$

Joh C, et al 2019 [60]

$$T_{cr} = 2A_o t\left[0.33\sqrt{f_{ck}}\right] \qquad \dots\dots\dots\dots\dots (14)$$

CSA A23.3-19 [61]

$$T_{cr} = \lambda 0.25\left[0.33\sqrt{f'_c}\right] A_o t \qquad \dots\dots\dots\dots\dots (15)$$

Xin Z, et al, 2021 [62]

$$T_u = 0.37 W_{tp} f_t + 0.11\sqrt{\xi}\frac{A_{stl} A_{con} f_{yv}}{s} + 0.22 w_t f_t \qquad \dots\dots\dots\dots (16)$$

Eurocode-2 [63]

$$T_{EU} = 2A_k \sqrt{\frac{A_{sw} f_{ywd}}{s}} \sqrt{\frac{A_{sl} f_{yld}}{u_k}} \qquad \dots\dots\dots\dots (17)$$

Australian Standard (AS3600) [64]

$$T_{AS} = f_{ys}\left(\frac{A_{sw}}{s}\right) 2A_t \cot\theta \qquad \dots\dots\dots\dots (18)$$

Turkish Standard (TS500) [65]

$$T_{TS} = \left(\frac{A_{sw} 2A_k f_{ywd}}{s}\right) \text{ .... } (19)$$

6. Comparison of Experimental Torsion in Building Code

The research findings on applied torsional forces on reinforced concrete beams are compared with the American (ACI318-19) code [35], Koutchoukali [50], and Hsu [49], table (2).

Table 2: Comparison among References and ACI 318-19, Koutchoukali and Hsu.

SOLID BEAMS											
Ref. s	**Beams Code**	**Diemensions**		**f'_c MPa**	**$T_{cr})_{exp}$ KN.m**	**$T_{cr})_{ACI-19}$ KN.m**	**$T_{cr})_{Koutchoukali}$ KN.m**	**$T_{cr})_{Hsu}$ KN.m**	**$\frac{Tcr)exp}{Tcr)ACI}$**	**$\frac{Tcr)exp}{Tcr)kouchoukali}$**	**$\frac{Tcr)exp}{Tcr)Hsu}$**
		b (mm)	**h (mm)**								
Waryosh W. A, et al 2015 [66]	STN	170	240	21	6.25	3.07	4.28	4.65	2.04	1.46	1.34
	STh	170	240	57	12.5	5.06	7.05	7.66	2.47	1.77	1.63
Behera, G. C, et al, 2016 [67]	U3N	125	250	35	5.53	2.54	3.54	3.85	2.18	1.56	1.44
	U4N	125	250	35	5.61	2.54	3.54	3.85	2.21	1.58	1.46
	U5N	125	250	35	5.615	2.54	3.54	3.85	2.21	1.59	1.46
	LO3N	125	250	35	5.816	2.54	3.54	3.85	2.29	1.64	1.51
	LO4N	125	250	35	5.816	2.54	3.54	3.85	2.29	1.64	1.51
	LO5N	125	250	35	5.816	2.54	3.54	3.85	2.29	1.64	1.51
Mohamed, H, and Benmokrane, B, 2016 [68]	BS-W	250	600	39.38	25.58	34.28	47.78	51.94	0.75	0.54	0.49
	BS120a	250	600	39.38	26.78	34.28	47.78	51.94	0.78	0.56	0.52
	BG-W	250	600	41.47	23.11	35.31	49.22	53.49	0.65	0.47	0.43
	BG120a	250	600	41.47	27.46	35.31	49.22	53.49	0.78	0.56	0.51
	BG60	250	600	39.25	27.76	34.25	47.75	51.90	0.81	0.58	0.53
	BC-W	250	600	38.5	28.62	33.89	47.25	51.35	0.84	0.61	0.56
	BC120	250	600	38.5	30.45	33.89	47.25	51.35	0.90	0.64	0.59
	BC60	250	600	39.25	30.14	34.25	47.75	51.90	0.88	0.63	0.58
Aziz, A., and Hashim, O. 2018 [69]	SB	220	350	38	7.5	10.58	14.75	16.03	0.71	0.51	0.47
Mohaisen, S. K 2020 [70]	BR-FC30-e1	100	200	30	16.5	1.205	1.68	1.83	13.69	9.82	9.04
	BR-FC30-e2	100	200	30	16	1.205	1.68	1.83	13.28	9.53	8.76
	BR-FC60-e1	100	200	60	25.5	1.704	2.38	2.58	14.96	10.74	9.88
	BR-FC60-e2	100	200	60	28	1.704	2.38	2.58	16.43	11.79	10.85
Kim, M. J., et al, 2020 [71]	S0	400	600	35.4	52	57	79.45	86.36	2.09	0.65	0.60
	SO8-3-65	400	600	35.4	68	57	79.45	86.36	2.73	0.86	0.79
	SO8-4-90	400	600	35.4	84	57	79.45	86.36	3.38	1.06	0.97
	SO8-5-122.5	400	600	35.4	61	57	79.45	86.36	2.45	0.77	0.71
	S10-3-52.5	400	600	35.4	69	57	79.45	86.36	2.77	0.87	0.80
	S10-4-72.5	400	600	35.4	57	57	79.45	86.36	2.29	0.72	0.66
	S-10-5-100	400	600	35.4	70	57	79.45	86.36	2.81	0.88	0.81
	S06-3-90	400	600	35.4	69	57	79.45	86.36	2.77	0.87	0.80
	S10-5-90	400	600	35.4	60	57	79.45	86.36	2.41	0.76	0.69
	S08-3-72.5	400	600	35.4	51	57	79.45	86.36	2.05	0.64	0.59
	S12-5-72.5	400	600	35.4	63	57	79.45	86.36	2.53	0.79	0.73
Rasheed, M. M. 2022 [72]	NC20	100	200	31	5.44	1.22	1.71	1.86	4.44	3.19	2.93
	NC25	150	250	31	6.9	3.23	4.50	4.89	2.14	1.53	1.41
	SC20	100	200	72	7.07	1.87	2.60	2.83	3.79	2.72	2.50
	SC25	150	250	72	10.35	4.92	6.86	7.46	2.10	1.51	1.39
	ST25	150	250	72	9.2	4.92	6.86	7.46	1.87	1.34	1.23
El-Mandouh, M. A., et al 2022 [73]	B0	150	300	30	4.41	4.0668	5.67	6.16	1.08	0.78	0.72
	B1	150	300	30	6.56	4.0668	5.67	6.16	1.61	1.16	1.06
	B2	150	300	30	6.78	4.0668	5.67	6.16	1.67	1.20	1.10
	B3	150	300	30	8.38	4.0668	5.67	6.16	2.06	1.48	1.36
	B4	150	300	30	10.24	4.0668	5.67	6.16	2.52	1.81	1.66
	B5	150	300	30	12.36	4.0668	5.67	6.16	3.04	2.18	2.01

Sultan, W., and Zghair, L. 2024 [74]	B0	150	200	110.42	-	4.458	6.21	6.75	-	-	-
	B0.5	150	200	110.42	4.88	4.458	6.21	6.75	1.09	0.79	0.72
	B1	150	200	110.42	7.35	4.458	6.21	6.75	1.65	1.18	1.09
	B-	150	200	110.42	7.95	4.458	6.21	6.75	1.78	1.28	1.18
	C0	150	200	110.42	-	4.458	6.21	6.75	-	-	-
	C0.5	150	200	110.42	5.1	4.458	6.21	6.75	1.14	0.82	0.76
	C1	150	200	110.42	7.5	4.458	6.21	6.75	1.68	1.21	1.11
	C-	150	200	110.42	8.4	4.458	6.21	6.75	1.88	1.35	1.24
	D0	150	200	110.42	-	4.458	6.21	6.75	-	-	-
	D0.5	150	200	110.42	5.25	4.458	6.21	6.75	1.18	0.84	0.78
	D1	150	200	110.42	8.25	4.458	6.21	6.75	1.85	1.33	1.22
	D-	150	200	110.42	8.78	4.458	6.21	6.75	1.97	1.41	1.30
Mean									**2.93**	**1.88**	**1.73**
S.D									**3.51**	**2.58**	**2.37**
COV%									**120%**	**137%**	**137%**

HOLLOW BEAMS

Ref. s	**Beams Code**	**Diemensions**		f'_c **MPa**	$T_{cr})_{exp}$ **KN.m**	$T_{cr})_{ACI-19}$ **KN.m**	$T_{cr})$ Koutchoukali **KN.m**	$T_{cr})_{Hsu}$ **KN.m**	**Tcr)exp / Tcr)ACI**	**Tcr)exp / Tcr)kouchoukali**	**Tcr)exp / Tcr)Hsu**
		b (mm)	**h (mm)**								
Mahdi, H. M.2015 [75]	B1	300	300	45.48	6.5	3.85	5.36	5.83	1.69	1.21	1.12
	B2	300	300	45.05	8.13	3.83	5.34	5.80	2.12	1.52	1.40
	B3	300	300	46.07	9.75	3.87	5.40	5.86	2.52	1.81	1.66
	B4	300	300	44.54	13	3.81	5.30	5.77	3.42	2.45	2.25
	B5	300	300	45.31	16.25	3.84	5.35	5.82	4.23	3.04	2.79
	B6	300	300	44.8	19.5	3.82	5.32	5.78	5.11	3.67	3.37
Waryosh, W. A., et al 2015 [66]	HTNC1	170	240	21	5	1.45	2.02	2.19	3.45	2.48	2.28
	HTNR1	170	240	21	3.75	1.43	2.00	2.17	2.62	1.88	1.73
	HTNR2	170	240	21	3.75	1.06	1.47	1.60	3.55	2.55	2.34
	HThC1	170	240	57	8.75	2.39	3.33	3.61	3.67	2.63	2.42
	HThR1	170	240	57	7.5	2.36	3.29	3.58	3.18	2.28	2.10
	HThR2	170	240	57	6.25	1.74	2.43	2.64	3.59	2.58	2.37
Aziz, A., & Hashim, O. 2018 [69]	HB-0D	220	350	38	5.25	2	3.33	4	2	1.58	1
	HB-2CD	220	350	38	8.25	2	3.33	4	3	2.48	2
	HB-2OD	220	350	38	6.75	2	3.33	4	3	2.03	2
	HB-4CD	220	350	38	10.5	2	3.33	4	4	3.15	3
	HB-4OD	220	350	38	9.75	2	3.33	4	4	2.93	3
Abdallah, M. H., & Aziz, A. H. 2018 [76]	B-R	300	300	41.3	5.625	6.25	8.71	9.46	0.90	0.65	0.59
	B-1.0X	300	300	41.3	6.25	6.25	8.71	9.46	1.00	0.72	0.66
	B-3.0X	300	300	41.3	6.75	6.25	8.71	9.46	1.08	0.78	0.71
	B-5.0X	300	300	41.3	7.5	6.25	8.71	9.46	1.20	0.86	0.79
	B-1.0XW	300	300	41.3	6.625	6.25	8.71	9.46	1.06	0.76	0.70
	B-3.0XW	300	300	41.3	7.25	6.25	8.71	9.46	1.16	0.83	0.77
	B-5.0XW	300	300	41.3	7.875	6.25	8.71	9.46	1.26	0.90	0.83
Kim, M. J., et al, 2020 [71]	H0	400	600	36.5	67	58	80.85	87.88	1.16	0.83	0.76
	H08-3-65	400	600	36.5	54	58	80.85	87.88	0.93	0.67	0.61
	H08-4-90	400	600	36.5	71	58	80.85	87.88	1.22	0.88	0.81
	H08-5-100	400	600	36.5	60	58	80.85	87.88	1.03	0.74	0.68
	H10-3-52.5	400	600	36.5	64	58	80.85	87.88	1.10	0.79	0.73
	H10-4-72.5	400	600	36.5	63	58	80.85	87.88	1.09	0.78	0.72
	H10-5-80	400	600	36.5	56	58	80.85	87.88	0.97	0.69	0.64
	H06-3-90	400	600	36.5	60	58	80.85	87.88	1.03	0.74	0.68
	H06-5-135	400	600	36.5	61	58	80.85	87.88	1.05	0.75	0.69
	H06-3-72.5	400	600	36.5	56	58	80.85	87.88	0.97	0.69	0.64
	H12-5-72.5	400	600	36.5	56	58	80.85	87.88	0.97	0.69	0.64
Aziz, A. H., and Abdallah, M. H. 2021 [77]	RB a	300	300	41.3	5.625	3.66	5.11	5.55	1.53	1.10	1.01
	1.0K-B	300	300	41.3	7	3.66	5.11	5.55	1.91	1.37	1.26
	3.0K-B	300	300	41.3	8.375	3.66	5.11	5.55	2.29	1.64	1.51
	5.0K-B	300	300	41.3	8.75	3.66	5.11	5.55	2.39	1.71	1.58

Mean	**2.11**	**1.53**	**1.41**
S.D	**1.20**	**0.88**	**0.83**
COV%	**57%**	**57%**	**59%**

7. Result And Discussion

The value of the average for the results that adopted the ACI318-19 code equation ($T_{cr})_{exp}/T_{cr})_{ACI}$) for solid and hollow sections is 2.93 and 2.11, respectively. As for the two equations used for comparison (Kouchoukali $T_{cr})_{exp}/T_{cr})_{kouchoukali}$) and (Hsu $T_{cr})_{exp}/T_{cr})_{Hsu}$) for the solid and hollow sections, they are (1.88 and 1.73) and (1.53 and 1.41), respectively. The coefficient of variation (COV) for hollow beams was decreasing when compared to solid beams for ACI code and Kouchoukali and Hsu equations, and they were (57%, 57%, and 59%), respectively, for hollow sections, and for solid sections they were (120%, 137%, and 137%) for ACI code and Kouchoukali and Hsu equations, respectively.

7.1 Effect of Types of Cross-Section

It was observed from the results obtained from the table (2) that all results for three equations are close, whether the section is hollow or solid. It was observed that using three equations in table (2) for hollow sections yielded more accurate results compared to using the same equations for solid sections. It was found that the coefficient of variation (COV) percentage of solid sections is higher than that of hollow sections by amounts of (63, 80, and 78) % according to the equations of (ACI318-19) code [35], Koutchoukali [50], and Hsu [49], respectively. Table (3) and figure (4) shows the percentage increase (COV %) for solid sections compared to hollow sections. This indicates that the equations used provide more accurate results for hollow sections, and American code is mentioned when used for hollow sections. Therefore, it turns out that using same equations for solid sections does not yield accurate results In addition; the reason for the large differences may be due to the variation in the amount of reinforcing steel used or the effect of the cross-section, as the sections vary in size according to the research used.

Table 3: Percentage Increase (COV%) for Solid Sections Compared to Hollow Sections

Coefficient Of Variation	Solid Section (COV%)	Hollow Section (COV%)	Increasing %
ACI318-19	120	57	63
KOUTCHOUKALI	137	57	80
HSU	137	59	78

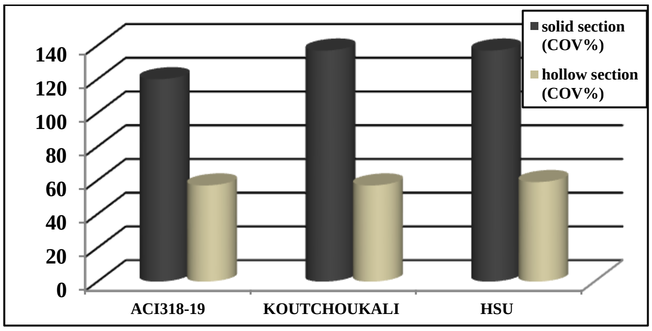

Figure 4: shows the percentage increase (COV%) for solid sections compared to hollow sections.

8. Conclusion

1. When comparing the researchers' validated results with those based on the American standard and Hsu and Kouchoukali's sources, it discovered that the critical torsion values varied, regardless of how big the difference was. The variables employed in the study or the use of beams with carbon bars or fiberglass may be to blame for this, as they may have an impact on the findings.
2. Therefore, it turns out that using same equations for solid sections does not yield accurate results. This indicates that the equations used provide more accurate results for hollow sections, and American code is mentioned when used for hollow sections.
3. According to the ACI code and the Kouchoukali and HSU equations, the coefficient of variation (COV) for hollow beams was declining in comparison to solid beams.
4. It was also found that the American code equation provides more conservatism in

design, and the value of the coefficient of variation (COV %) is lower, which indicates accuracy in giving results whether the section is hollow or solid.

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Abbreviation

T_{cr} = critical torsion.
f_c' = compressive strength of concrete.
A_{cp} = area of concrete cross-section.
P_{cp} = surround of the concrete section.
T_n = nominal torsion.
T_u = ultimate torsion.
T_{EU} = torsion depend on euros code.
T_{AS} = torsion depend on Australian code.
T_{TS} = torsion depend on Turkish code.
ACI = American concrete institute standard.
CSA =Canadian standard association standard.
GFRP = glass fiber reinforced concrete.
CFRP = carbon fiber reinforced concrete.
b = width.
h =high.
t = thickness.
A_o = region that the shear flow path encloses.
λ = modification factor.
H = hollow section.
NOST = Webs made of corrugated steel.
CBGCSWs = Composite box-girders with corrugated steel webs.

Conflict of Interest

Writers want to emphasize that no conflict of interest exists resulting from the article's publication.

Author Contribution Statement

To create a useful research paper for researchers that would direct them in the field of review and information gathering, the authors helped compile and summarize a large number of sources and thoroughly examine the suggested topic from all angles.

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