Tikrit Journal of Engineering Sciences (2025); 32(1): 1790

DOI: http://doi.org/10.25130/tjes.32.1.21

IRAQI Academic Scientific Journals

ISSN: 1813-162X (Print); 2312-7589 (Online)

Tikrit Journal of Engineering Sciences

available online at: http://www.tj-es.com

TJES Tikrit Journal of Engineering Sciences

The Torsional Behavior of Transversely Opened Reinforced Concrete Beams Strengthened by Steel Pipe

Najla'a H. AL-Shareef**, *Ayoob A. Ibrahim*, *Hayder Al-Khafaji*, *Rafaa F. Hassan

Civil Department, Engineering College, Babylon University, Babylon, Iraq.

Keywords:

Concrete Beams; Orientation; Steel pipe; Transverse opening; Torsion.

Highlights:

- *Structural performance of Transverse opening Reinforced with a steel pipe.*
- *Structural performance of different steel pipe orientations on the final twisting moment and twist angle.*
- *Torsional was done using an experimental program.*

ARTICLE INFO

Article history:

Received	14 Oct. 2023
Received in revised form	09 Jan. 2024
Accepted	27 Jan. 2024
Final Proofreading	04 Dec. 2024
Available online	25 Mar. 2025

Citation: AL-Shareef NH, Ibrahim AA, Al-Khafaji H, Hassan RF. **The Torsional Behavior of Transversely Opened Reinforced Concrete Beams Strengthened by Steel Pipe**. *Tikrit Journal of Engineering Sciences* 2025; **32**(1): 1790. http://doi.org/10.25130/tjes.32.1.21

**Corresponding author:*

Najla'a H. AL-Shareef

Civil Department, Engineering College, Babylon University, Babylon, Iraq.

Abstract: One way to strengthen beams with transverse openings is by adding material, such as steel plates or braces, around the openings. This addition helps distribute the load more evenly and reduces stress concentration at the weak points. In this study, experimental investigations were conducted to evaluate the effectiveness of using steel pipes of different sizes and thicknesses to improve the torsional behavior of reinforced concrete beams with different sizes of transverse openings. Another goal is to investigate the impact of different steel pipe orientations on the final twisting moment and twist angle. The experiment involved casting and testing fifteen rectangular reinforced concrete beams under pure torsion. The dimensions and reinforcement of all beams were similar. The specimens were divided into four groups, the first of which had a control beam made of a single beam cast without any openings. Using 4 mm diagonal reinforcement applied to each face of the beam and rounding the opening with PVC pipe from the second group, two beams with varying opening diameters (75 and 100) mm were strengthened. The third group consists of four beams that were strengthened using steel pipe welding at a double angle (32×32×3) mm to form a T-section with two orientations (45° and 90°). These beams were cast with transverse apertures. Six beams were cast as the fourth group to study the thickness effect on steel pipe (2, 3, and 4) mm, representing 50%, 75%, and 100% of stirrups' nominal diameter. The results revealed that diagonal reinforcement with small openings did not affect torsional behavior. On the other hand, the diagonal reinforcement did not substitute for the missing torsional strength of the large opening in the beam. The ultimate torsional loads that result from the two orientations of steel pipes (45° and 90°) were almost identical. Also, internal pipe deformation is prevented by utilizing a steel pipe at least 3 mm thick (0.75 of the stirrups' diameter), increasing protection for this area. Hence, beams with small openings and beams with a pipe thickness of 4 mm (1.0 of the stirrups diameter) are similar in toughness and initial stiffness.

سلوك الالتواء للعتبات الخرسانية المسلحة المفتوحة بشكل عرضي والمقواة بأنابيب الصلب

نجلاء حميد آل شريف، ايوب ابراهيم، حيدر الخفاجي، رافع فليح حسن
قسم الهندسة المدنية/ كلية هندسة / جامعة بابل / بابل – العراق.

الخلاصة

تتمثل إحدى طرق تقوية الاعتاب ذات الفتحات المستعرضة في إضافة مواد إضافية، مثل الألواح الفولاذية أو دعامات، حول الفتحات. ان هذا يساعد على توزيع الحمل بالتساوي ويقلل من تركيز الإجهاد عند نقاط الضعف. هذه الدراسة، أجريت تحريات عملية لتقييم فعالية استخدام الأنابيب الفولاذية بأحجام وسمك مختلفة لتحسين السلوك الالتوائي لعتب الخرسانة المسلحة بأحجام مختلفة من الفتحات العرضية. الهدف الآخر هو دراسة أثر تغيير اتجاه دوران الانبوب الفولاذي على اقصى عزم الدوران وزاوية الدوران. يتضمن العمل المختبري خمسة عشر عتب خرسانية مستطيلة الشكل تم صبها واختبارها تحت دوران صافي. جميع الاعتاب لها أبعاد مماثلة بالأبعاد والتسليح. تم تقسيم العينات إلى أربع مجموعات، كان أولها يحتوي على عتب مرجعي مصنوعة من حزمة واحدة تم صبها بدون فتحات باستخدام تسليح قطره ٤ ملم مطبقة على كل وجه من جوانب العتب وتم تعزيز الفتحة بأنبوب PVC بأقطار مختلفة (٧٥ و ١٠٠ ملم) متمثلة بالمجموعة الثانية. تتكون المجموعة الثالثة من أربع اعتاب تم تقويتها باستخدام مقاطع فولاذية بزاوية مزدوجة (٣٢*٣٢*٣) ملم تم لحامها معا لتشكيل مقطع T بزاويتي دوران (٤٥° و٩٠°). لدراسة تأثير السمك على الأنابيب الفولاذية (٢ و ٣ و ٤ ملم) والتي تمثل ٠,٥ و ٠,٧٥ و ١,٠ من قطر تسليح القص، تم صبها بستة اعتاب كمجموعة رابعة. وكشفت النتائج أنه لم يكن هناك أي تأثير على السلوك الالتوائي نتيجة لاستخدام التسليح القطري مع فتحات صغيرة. من ناحية أخرى، لم يحل التسليح القطري محل القوة الالتوائية المفقودة للفتحة الكبيرة في العتب كانت الأحمال الالتوائية النهائية الناتجة عن اتجاهي الأنابيب الفولاذية (٤٥° و٩٠°) متطابقة تقريبا. أيضا، من خلال استخدام أنابيب الفولاذ التي لا تقل عن سمك ٣ ملم (٠,٧٥ من قطر تسليح القص)، يتم منع التشوه الداخلي، مما يؤدي إلى زيادة الحماية لهذه المنطقة. ومن ثم، فإن الاعتاب ذات الفتحات الصغيرة والتقوية بسمك أنبوب فولاذي ٤ ملم (١,٠ من قطر تسليح القص) متشابهة لأغراض الخشونة والصلابة الأولية.

الكلمات الدالة: العتبات الخرسانية، أنابيب فولاذية، فتحات عرضية، التواء، اتجاه.

1.INTRODUCTION

Pipes and ducts are usually less aesthetic; they are placed under the beam and covered by a suspended ceiling., These ducts and pipes pass within transverse openings in the floor beams. The total height of a multistory building can be decreased since transverse openings, making it possible for pipes and ducts to pass through it [1]. In fact, beams frequently have web holes to make it easier for environmental services to pass through. These apertures might be of different shapes and sizes [2]. Additionally, the openings distort or alter the usual stress flow, causing fast cracking and stress concentration in the opening area. To control cracking widths and prevent early beam failure, special enclosing or reinforcing of the aperture along its periphery, the same as any discontinuity, should be provided. Web openings are divided into small and large openings based on their size and location, and their size decides the best position for each. Web holes have been shown to take the shapes of circles, rectangles, diamonds, triangles, trapezoids, and even irregular shapes. The most typical opening shapes are round and rectangular [3]. Using reinforced Reactive Powder Concrete (RPC) T-section beams with rounded and square web openings, the torsional behavior of the beams was examined by Alamli et al. [4]. Ten T-beams with circular and square web openings were cast and tested using reactive powder concrete (RPC). The outcomes revealed that as the opening became larger, crack density loss became non-uniform, but ultimate torques decreased. Furthermore, the torque capacity of the web beams with similar dimensions was decreased due to non-uniformity in the distribution of shear stress caused by the opening eccentricity. The results demonstrated that as opening size loss, final torques reduced, and crack density increased and became uneven. Additionally, the irregularity of the opening caused an uneven distribution of shear stress across the web, reducing the torque capacity. The stiffness of the reinforced concrete beams can be decreased by transverse openings, thereby decreasing its resistance to flexure, torsion, and shear [5]. Strengthening such as those in this case to enhance the torsional behavior of reinforced concrete beams will be using steel pipes as a strengthening technique. Several studies have investigated the effect of transverse opening reinforced concrete beams under pure torsion have been done. Abdo and Mabrouk [6] investigated the behavior of simply supported reinforced concrete beams with an opening under pure torsion. The main parameters of the study were the number of openings, the spacing between stirrups, and the beam depth. The experimental work resist of torsion-only loading on seven beams with 1800 mm clear span length and 150 mm beam width were constant for all beams. The first beam was solid and used as a standard compared to other beams, divided into three groups based on a parameter and opened. The test results illustrated that the rise in openings decreased torsional capacity. While for beams with one opening, the ultimate rotation angle rose by 20%, and for beams with two openings, it increased by 34%. For spacing between stirrups changing from 165-100 mm, the increase in torsional capacity was about 32% for ultimate torque. The results also showed that the increase in torsional capacity was 25% for the beam depth change from 300 to 400 mm. Chiu et al. [7] studied the experimental analysis of crack patterns, maximum crack width, torsional ductility, torsional strength, and post-cracking reserve strength in high-strength concrete and NSC beams. It found that post-cracking strength reserve was influenced by reinforcement ratio, torsional strength, and aspect ratio. Additionally, according to the researchers, a rise in the aspect ratio of the beam cross-section was linked to a decrease in cracking and an increase in ultimate strength. Hassan et al. [8,9] have also provided numerous theoretical methods to evaluate fiber-reinforced concrete beams' maximum torque and breaking torque under a pure torsion load. Teixeira and Bernardo [10] collected and analyzed different experimental results of the torsional ductility of rectangular cross-section reinforced concrete (RC) beams. Various parameters were studied, such as a plain or hollow cross-section, the compressive strength of concrete, and the effect of reinforcement ratio on torsion. The effect of every variable study on the ductility of torsion was investigated, and significant results were pointed out that might help with the (RC) beams design under torsion. Also studied a relative analysis with principles of code. They concluded that the torsional ductility increased with the compressive strength in plain (RC) beams, while the hollow (RC) beams decreased. Also, it was observed that the torsional ductility decreased with the increase in the total torsional reinforcement ratio. Ling et al. [11] studied the performance of circular-opening RC beams. In the experimental program, eleven RC beams with identical dimensions were studied. The results demonstrated that the aperture, particularly in large openings, affected the beam's yield strength, stiffness, ductility, and ultimate strength. With a beam height opening of 1/3, the diagonal bar strengthening technique strengthened the beam. Abdulrahman et al. [12] examined how a reinforced concrete T-beam with a circular opening performed under a pure torsional moment. The five beams used in the experiment all have the same dimensions and reinforcing. As a control, one of the beams was solid; the other two were cast with openings of various sizes (100 and 150 mm) and locations (Lc/2 and Lc/3). The test findings show that the T-beam with a 100mm diameter for a circular opening and varied dimensions has an ultimate torsional capacity of around (23% and 30%) less than the reference without an opening. In addition, the angle of twist for beams with opening diameters of 47% and 71% from total depth was enhanced compared to solid beams. According to Hekal et al. [13], the greatest results for resisting torsion loads came from strengthening and employing external steel plates fastened by both epoxy steel dowels. Twelve reinforced concrete T-beams were subjected to pure torsion to determine how well carbon fiber-reinforced polymer (CFRP) worked as an externally bonded reinforcement Atea [14]. However, Kandekar and Talikoti [15] used a rammed fiber as an externally bonded reinforcement by testing a twelve-reinforced concrete rectangular beam under a torsional moment. Recently, Nageh et al. [16] investigated the response of reinforced concrete beams under simultaneous torsion and bending. The experiments consist of full warping with continuous glass fiber reinforced polymer (GFRP) sheets and discrete GFRP strips with the same GFRP reinforced ratio. The results indicated that employing the GFRP warping sheet for strengthening significantly improved the overall performance of the strengthened beams. Jasim et al. [17] studied the impact of the openings on beams subjected to repeated loads. The Near Surface Mounted technique's (NSM) strength enhancement of the beams was quantified. In the experimental program, fifteen RC beams were cast and put to the test. The NSM technique was used to reinforce nine beams that had circular transverse openings in varied places. Six, three without reinforcing and three with strengthening, were used as control beams without apertures. Each beam was tested under three different loads: monotonic (for control beams), incremental repeated load, and constant repeated load. All beams have similar sizes and strengthening. The findings demonstrated that repeated loads impacted all beams with transverse openings when the twist angle increased, and the maximum torque dropped. The openings significantly affected the maximum torque reduction; however, the beam's ultimate torsional capacity decreased by 43.83% when subjected to constant, repeated loads and had its opening at one-fourth of the clear span. Moving the opening position away from the supports significantly enhanced the final torque. Additionally, compared to non-strengthened beams, strengthening minimized or reduced the effect of openings on the final torque.

2.RESEARCH OBJECTIVE

This study's main objective is to ascertain whether adding steel pipe of various sizes and thicknesses can successfully enhance the torsional behavior of reinforced concrete beams with various transverse opening sizes. Another goal of this study is to investigate the impact of different steel pipe orientations on the maximum twisting moment and twist angle.

3.EXPERIMENTAL PROGRAM

This research used an internal strengthening technique to enhance the behavior of reinforced concrete beams under pure torsion. The effects of the size of the transverse opening, the effect of orientation, and the thickness of the steel pipe were all investigated.

3.1.Experimental Procedure

In the lab, pure torsion tests were performed on a total of fifteen rectangular reinforced concrete beams. The beams were made with dimensions of (150*200*1200)mm and were designed in accordance with ACI [18] for structural research. For torsional, all the beams were reinforced with 2-Ø12mm bars on top and bottom layers and Ø4 mm bars at 50mm spacing for stirrups along the span, while the spacing between stirrups at the support was 33mm to avoid local failure, as shown in Fig. 1. The specimens were divided into four groups: the first group consisted of one beam, cast without opening as a control beam. Two beams with different opening sizes (75 and 100) mm were strengthened by applying 4mm diagonal reinforcement on each face of the beam and rounding the opening with PVC pipe that referred to the second group, as shown in Fig. 2. The third group contains four beams, cast with transverse openings strengthened using steel pipe welding at a double angle (32×32×3) mm to form a T-section with two orientations (45°and 90°), as shown in Fig. 3. To study the thickness effect on steel pipe (2, 3, and 4) mm, representing 50%, 75%, and 100% of stirrups' nominal diameter, six beams were cast as the fourth group. Table 1 shows the specimens' details.

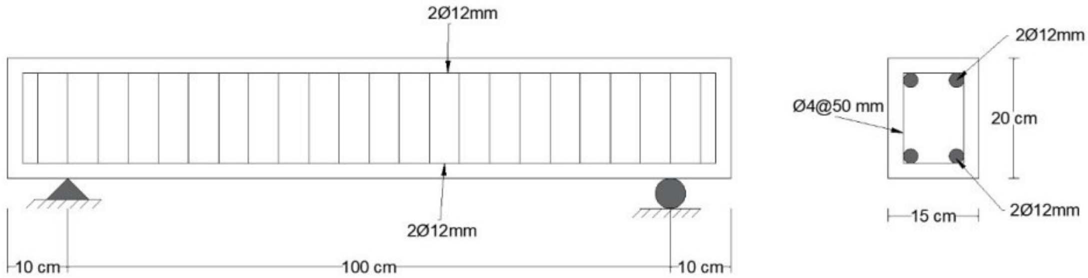
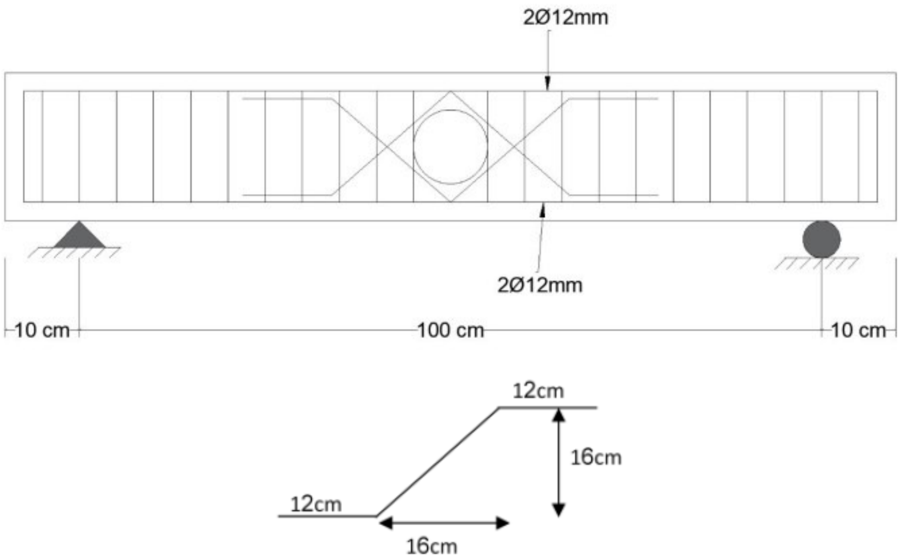
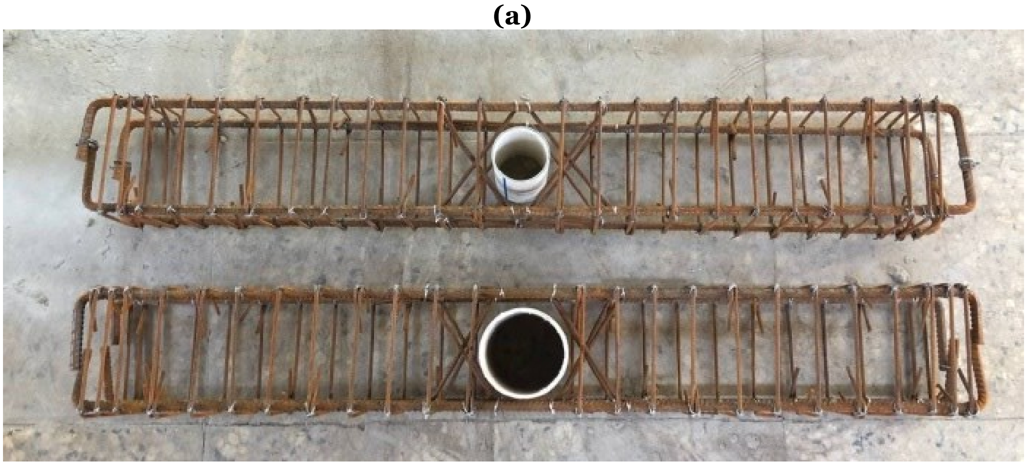


Fig. 1 Details of the Beam.

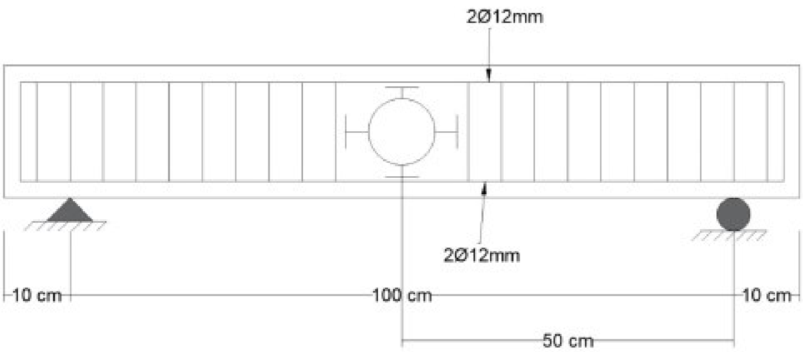


(a)

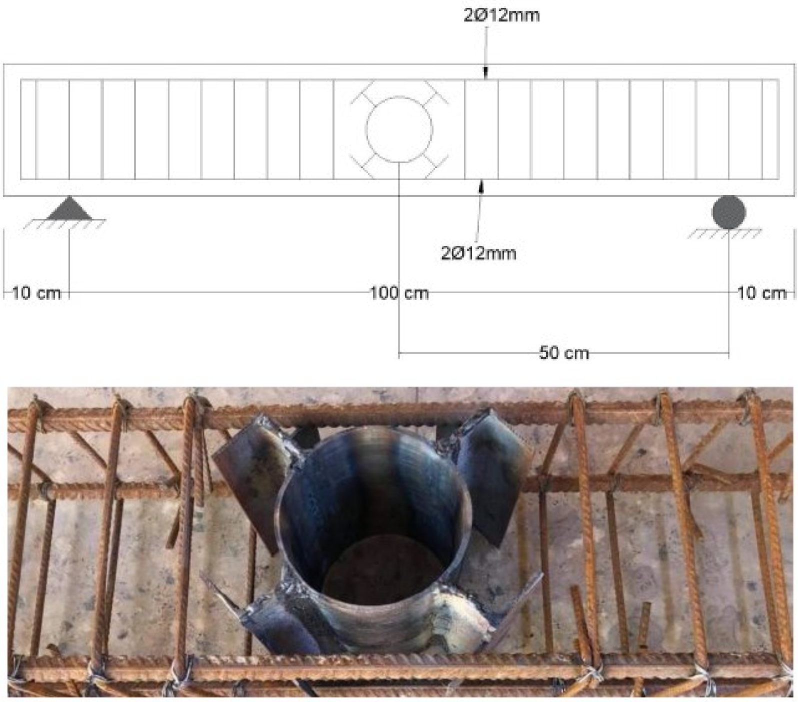


(b)

Fig. 2 Beam with Opening a) Details of Reinforcement b) Casted Beam.



(a)



(b)

Fig. 3 Beam with Steel Pipe (a) with 90° Orientation, (b) with 45° Orientation.

Table 1 The Specimen Details.

Specimen identify-cation	Description
CB	Reference reinforced concrete beam.
P75	Reinforced concrete beam containing circular opening of PVC Pipe with a diameter of 75mm (small opening, S).
P100	Reinforced concrete beam containing circular opening of PVC Pipe with a diameter of 100mm (large opening, L).
S2-90	Reinforced concrete beam containing small circular opening of steel Pipe of 2mm thickness with 90° orientation.
L2-90	Reinforced concrete beam containing large circular opening of steel Pipe of 2mm thickness with 90° orientation.
S3-90	Reinforced concrete beam containing small circular opening of steel Pipe of 3mm thickness with 90° orientation.
L3-90	Reinforced concrete beam containing large circular opening of steel Pipe of 3mm thickness with 90° orientation.
S4-90	Reinforced concrete beam containing small circular opening of steel Pipe of 4mm thickness with 90° orientation.
L4-90	Reinforced concrete beam containing large circular opening of steel Pipe of 4mm thickness with 90° orientation.
S2-45	Reinforced concrete beam containing small circular opening of steel Pipe of 2mm thickness with 450 orientation.
L2-45	Reinforced concrete beam containing large circular opening of steel Pipe of 2mm thickness with 450 orientation.
S3-45	Reinforced concrete beam containing small circular opening of steel Pipe of 3mm thickness with 450 orientation.
L3-45	Reinforced concrete beam containing large circular opening of steel Pipe of 3mm thickness with 450 orientation.
S4-45	Reinforced concrete beam containing small circular opening of steel Pipe of 4mm thickness with 450 orientation.
L4-45	Reinforced concrete beam containing large circular opening of steel Pipe of 4mm thickness with 450 orientation.

3.2.Materials

Several self-compact trail mixes are performed to select the mixture used to cast concrete rectangular beams. The mixture was cast into a (100×200)mm cylinder and tested according to ACI-211.1-14 [18]. After a 28-day treatment period, the compressive strength was 38.1 MPa. The mix weights are shown in Table 2.

Table 2 Properties of Concrete Mix.

Material	Mix
Water (kg/m^3)	190
Cement (kg/m^3)	500
Fine agg. (kg/m^3)	775
Coarse agg. (kg/m^3)	825
Superplasticizer (1/100 kg cement)	5

3.2.1.Cement

In this research, cement sulfate resistance type (V) was used with respect to IQS, NO.5/1984 [19]. The chemical analysis and Physical properties of cement are shown in Tables 3 and 4. Respectively.

3.2.2.Coarse Aggregate

Crushed gravel from Al-Nabai in Salah Al-Din was utilized in this investigation. The gravel gradient and properties were according to the requirement of IQS NO. 45/1984[20]. Table 5 shows the properties of coarse aggregate.

3.2.3.Fine Aggregate

Normal sand conforms to the limits of Iraqi Specification IQS NO. 45/1984[21] zone (2). Table 6 shows the properties of fine aggregate.

3.2.4.Steel Reinforcement Bars

In this research, two different diameters of deformed steel bars (12 and 4) mm were used. The yielding and ultimate strength were determined by tests according to ASTM A615-85[22], as presented in Table 7.

3.3.Test Procedure

Three cylinders and cubes were tested for mix following BS.1881: part 116.1989 [23], and ASTM A615-85 [22], to measure the splitting tensile and compressive strength at 28 days. All specimens were tested under pure torsion by applying point load at the center of a 2000 mm long steel girder with a diagonal cross-section utilizing a universal testing machine with a capacity of 480 kN and a constant loading rate. On the other hand, the steel girder is connected to the specimen by a 50-mm steel arm tightened by bolts on both sides of the beam, as shown in Fig. 4.

Table 3 Chemical Analysis for Cement.

Compound composition	Chemical composition	% by weight	Limits(IQS NO.5/1984)
Iron oxide	Fe2O3	5.22	----
Silica	SiO2	21.5	----
Lime	CaO	62.16	----
Alumina	Al2O3	4.05	----
Sulfate	SO3	1.99	<2.50
Magnesia	MgO	2.11	<%5.00
Lime saturation factor	L.S.F	0.95	0.66-1.02
Insoluble residue	I.R	0.9	<1.5
Loss on ignition	L.O.I	2.11	<4.00
Main compounds (Bogue's equs.)		**Percent by weight of cement**	
Tricalcium aluminate (C3A)		2.11	
Dicalcium silicate (C2S)		25.38	
Tricalcium silicate (C3S)		55.65	
Tetracalcium aluminoferrite (C4AF)		15.54	

Table 4 Physical Properties of Cement.

Physical properties	Test results	Iraqi specifications limits (I.O.S.5/1984)
Setting time (Vicat's method)		
Initial setting, hr: min	0:55	≥00:45
Final setting, hr: min	7:35	≤10:00
Fineness (Blaine Method), m^2/Kg	310	≥250
Compressive strength, MPa		
3 days	22.5	≥15:00
7 days	27.43	≥23:00
Soundness (Autoclave) method %	0.18	≤0.8

Table 5 Properties of Coarse Aggregate.

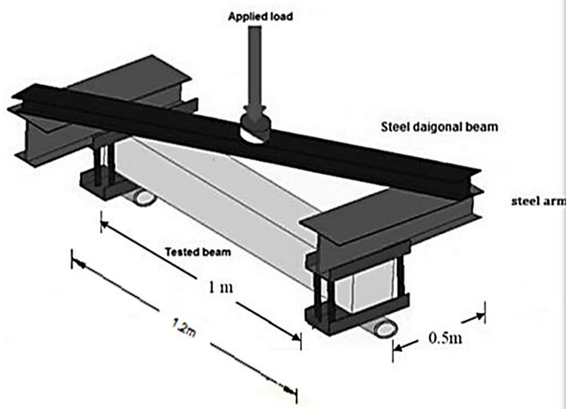
Sieve size	Passing % Cumulative passing	Limits of Iraqi Specification No.45/1984 Max (5-14) mm
20 mm	100	100
14 mm	100	90 – 100
10 mm	90	50 – 85
4.75 mm	10	0-10

Table 6 Properties of Fine Aggregate.

Properties	Test results	Limits of Iraqi specification No.45/1984 for the zone (2)
Specific gravity	2.77	_
Sulfate content SO3	0.13 %	≤0.5
Absorption	0.73 %	_

Table 7 Steel Bar Properties.

Bar size	Actual diameter(mm)	Yield stress (MPa)	Ultimate strength (MPa)
12	11.8	480	753
4	4.8	440	721



(a)

(b)

(c)

Fig. 4 (a) Test Set Up and (b) Instrumentation, (c) Support at Ends of the Beam.

Two 0.01mm accuracy dial gages were utilized at two beam's ends. As depicted in Fig. 5, the distance between the cross-section's center and the dial's placement was 150mm. At each loading interval, the twist angle and deflection readings were noted, as well as the load of the first crack loading and failure load. The angle of twist in reading was evaluated by dividing the summation of readings by two gages of 150mm, as shown in Fig. 6.

Fig. 5 Angle of Twist Measurement.

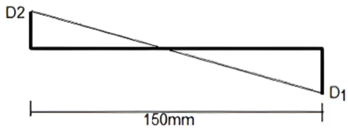


Fig. 6 A Sketch Showing How to Measure the Angle of Twist.

4.TEST RESULTS AND DISCUSSION

4.1.Mechanical Properties of Hardened Concrete

Table 8 shows the compressive, tensile strength, and other mechanical properties of concrete mix.

4.2.Torsional Strength Values

Table 9 lists the first cracking load, maximum torsional moment, and maximum twisting angle per unit length. Figure 7 displays the values of torsional moment vs. angle of twist per unit length for all beams. The torque-twisting angle is approximately linear until between (2.2 to 3.5) kN.m for all beams. Then, with a few small fine cracks observed, notable nonlinear curves with hardening behavior appeared. The softening behavior was noticeable after the ultimate torque was reached and continued to be monitored until the specimen approached failure. This result focuses on the effect of opening size changes due to the thickness or orientation of steel pipe. The effect of small openings on the maximum resistance is unclear because the inclined steel compensated for the decrease resulting from the loss of concrete through the opening. As for the large openings, the decrease became clear.

4.2.1.Effect of Opening Size

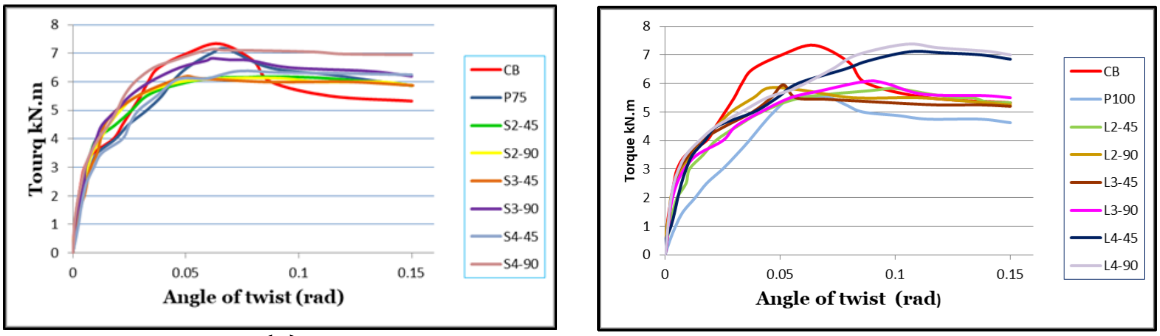
Torque and angle of twist relationship for beams with a small opening and large opening, as shown in Fig. 8. It can be concluded that the transverse opening size has the uttermost effect on the behavior and ultimate torque because of the decrease in the cross-sectional area that resists the applied torque, also decreases in torsional rigidity due to reduction in polar moment of inertia. According to the findings, increasing the opening size decreases the ultimate torque and initial cracking by 37.14% and 31%, respectively, for large openings, compared to tiny openings, which both show reductions of 22.85% and 25%, respectively.

Table 8 Mechanical Properties of Hardened Concrete.

Dry density of concrete kg/m³	Cylinders Compressive Strength "fc'"(MPa)	Cubic Compressive Strength "f_{cu}" (MPa)	Modulus of Rupture (MPa)	Splitting Tensile Strength (MPa)	Modulus of Elasticity (MPa)
2654	32.86	38.21	3.554	4.3	43455.41

Table 9 Results of Cracking and Ultimate Torque.

Specimen	First cracking torque, T_{cr} ($0.65T_{ult}$) (kN.m)	%T_{cr}	Ultimate torque, T_{ult} (kN.m)	(T_{ult}-T_{CB})*100%/ T_{ult}	(T_{cr}/T_{ult}) %
CB	3.5	-	7.34	-	47.7
P75	2.7	22.85	7.16	-2.5	37.7
P100	2.2	37.14	5.6	-31	39.3
S2-45	3	14.3	6.2	-18.4	48.4
S2-90	3	14.3	6.3	-16.5	47.6
L2-45	2.8	20	5.8	-27	48.3
L2-90	2.8	20	5.85	-26	47.8
S3-45	3	14.3	6.5	-12.9	46.2
S3-90	3.2	8.6	6.8	-7.4	47.1
L3-45	2.9	17	5.9	-24	49.2
L3-90	3	14.3	6.1	-20	49.2
S4-45	3.2	8.6	6.6	-11.2	48.5
S4-90	3.3	5.7	7.3	-6.6	45.2
L4-45	3	14.3	7.1	-3.4	42.3
L4-90	3.1	11.4	7.38	+0.5	42



(a) (b)

Fig. 7 Torque–Angle of Twist Relationship for All Beams, (a) Small Opening, (b) Large Opening.

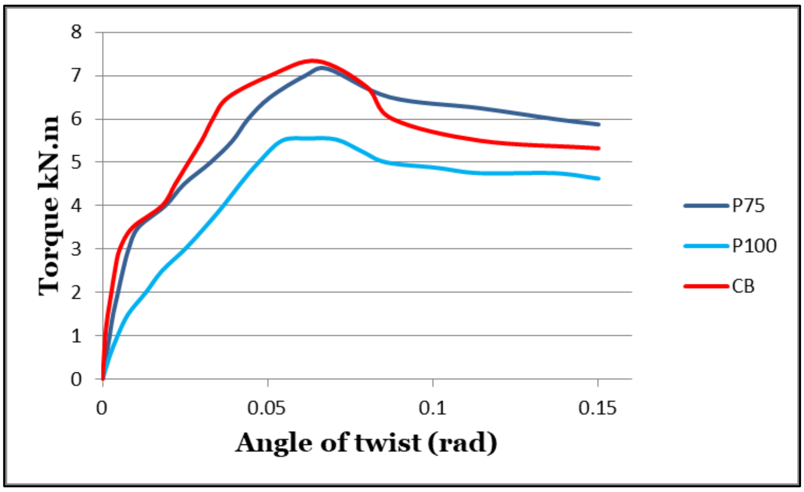


Fig. 8 Torque –Angle of Twist Relationship for Beams with a Small Opening and Large Opening.

4.2.2. Effect of Strengthening Technique and Orientation

The effect of strengthening is noticed by two techniques. The first technique uses four diagonal reinforced 4mm applied to each face of the beam around the opening, represented by P75 and P100. The second one used steel pipes with different orientations. Figure 9 and Table 10 show that using steel pipe with an orientation of 90° gives better results for resisting pure torsion than steel pipe with an orientation of 45°, and diagonal around the opening were increased by (4.46% and 3.6%), respectively, for a large opening. While in the small opening, the diagonal reinforcement increased by about (12% and 13.4%) to steel pipe with orientation 90° and 45°, respectively, for resisting pure torsion because the torsional cracks were at an angle of approximately 45° and did not contribute to the torsion resistance because they occurred along the length of the crack.

4.2.3. Effect of Steel Pipe Thickness

Using steel pipe with 4mm thickness in group four enhanced the results. The ultimate torque for S4-90 and S3-90 increased with respect to the S2-90 by about (15.87% and 7.35%), respectively, for a small opening, as shown in Fig. 10. It is also noticed that specimens with large openings gave an increase in torque with represent to the L2-90 about (26.15% and 0.85%) for L4-90 and L3-90, respectively. The impact of strengthening increased with the increase in steel pipe thickness due to utilizing more steel pipe thickness. This technique is therefore recommended for large transverse openings.

4.2.4. Crack Pattern

In the typical torsional failure mode, spiral diagonal cracks appeared at mid-span around the transverse opening, subjected to pure torsion. The spreading of cracks across a larger area was exhibited in the control beams compared to the beams with transverse openings because no diagonal reinforcement or steel pipe inhibited crack spreading. As a result of the decreased cross-sectional transverse area, failure and cracking occur at the weak zone represented by the transverse opening. Figures 11 and 12 display the failure mechanisms for each specimen. Using a large opening with increasing steel pipe thickness and 90° orientation in specimen L4-90 improved the results. Based on the other test results, these improvements are considered the best.

Table 10 Results of Strengthening Technique and Orientation.

Specimens (Large Opening)	Ultimate Torque (kN.m)	%	Specimens (Small Opening)	Ultimate Torque (kN.m)	%
P100	5.6	-	P75	7.16	-
L2-45	5.8	3.6	S2-45	6.2	12
L2-90	5.85	4.46	S2-90	6.3	13.4

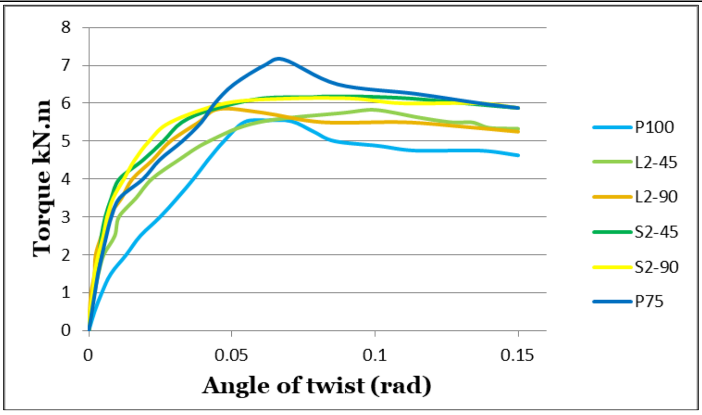


Fig. 9 Torque –Angle of Twist Relationship for Beams with Different Strengthening Techniques.

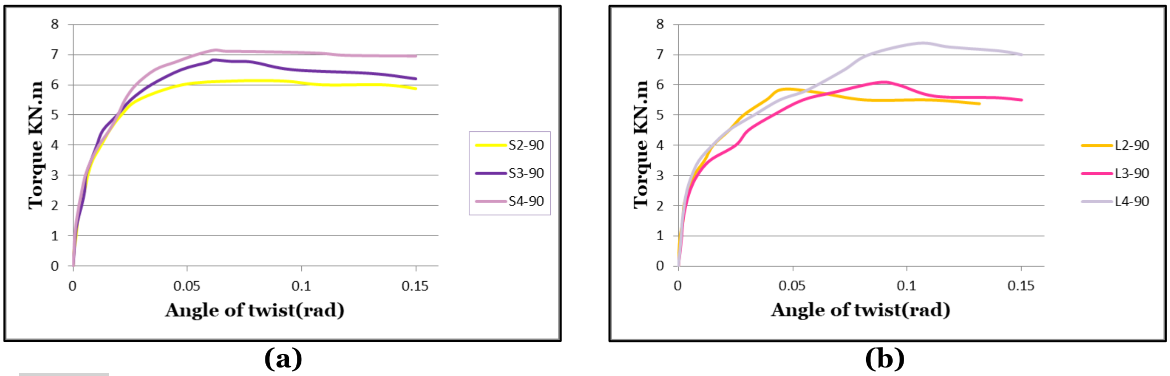


Fig. 10 Torque –Angle of Twist Relationship for Beams with Different Steel Pipe Thickness (a) Small Opening and (b) Large Opening.

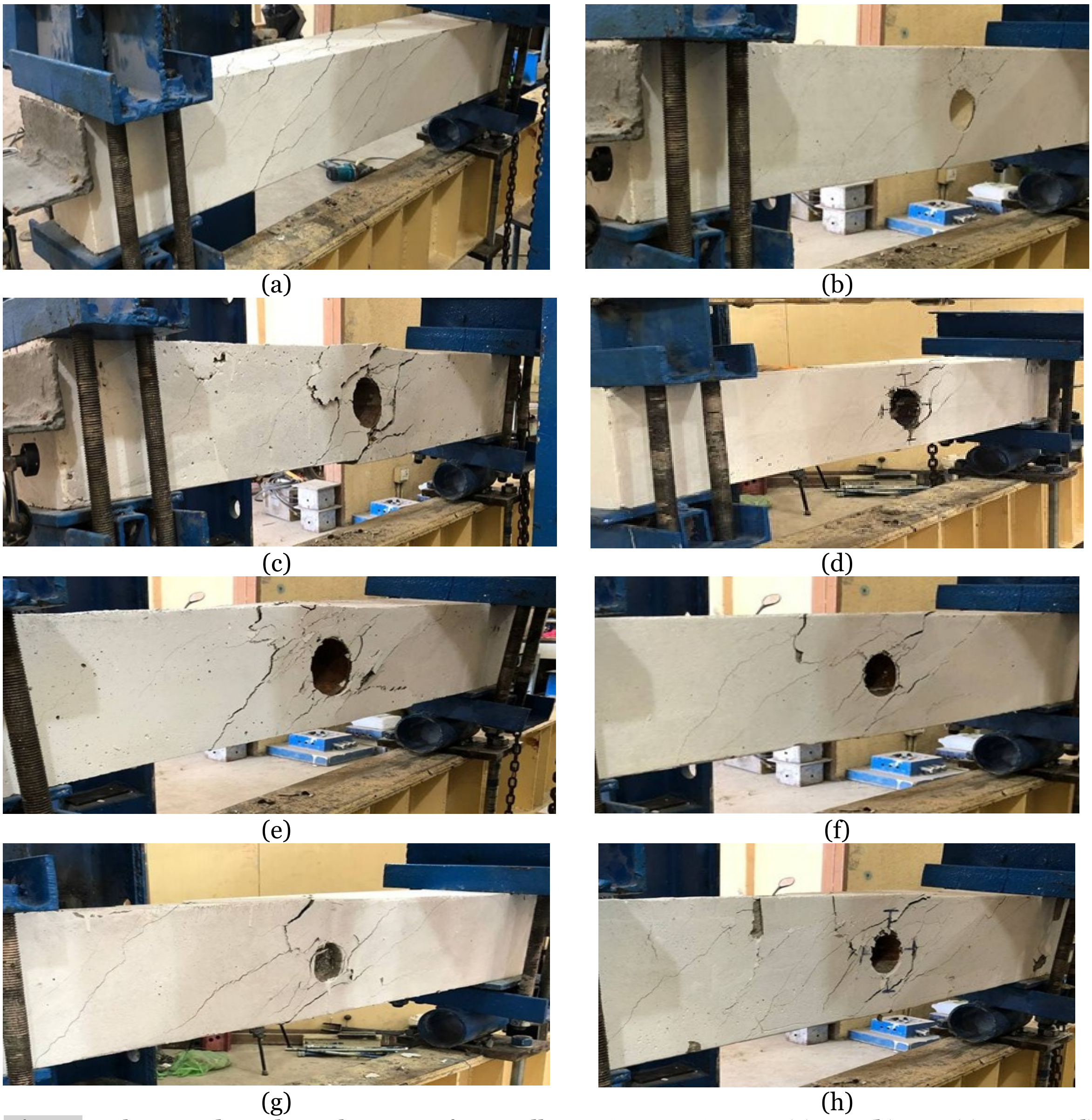
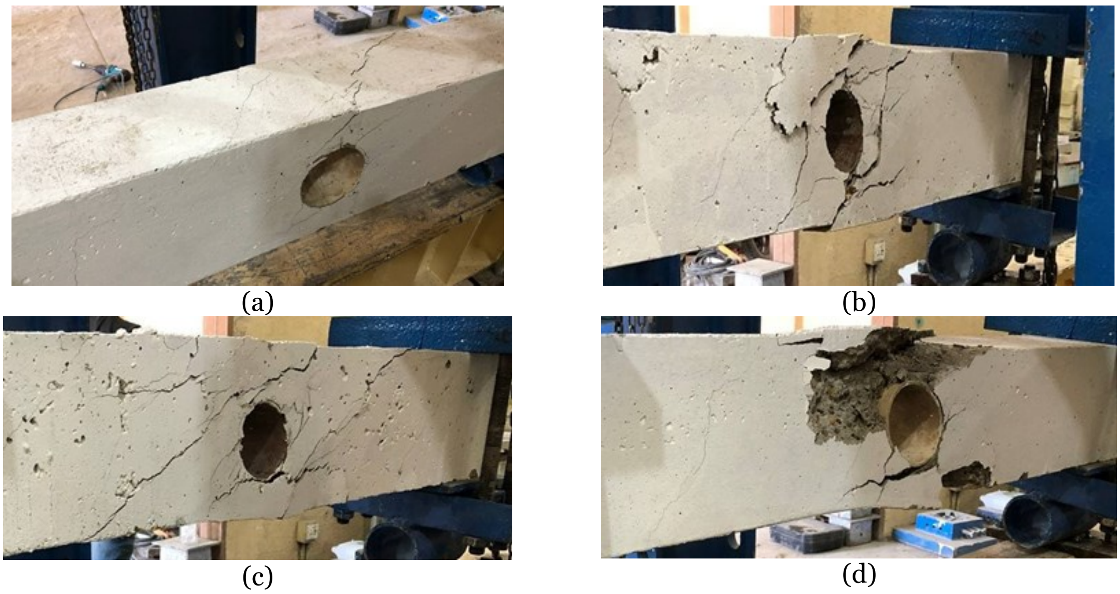
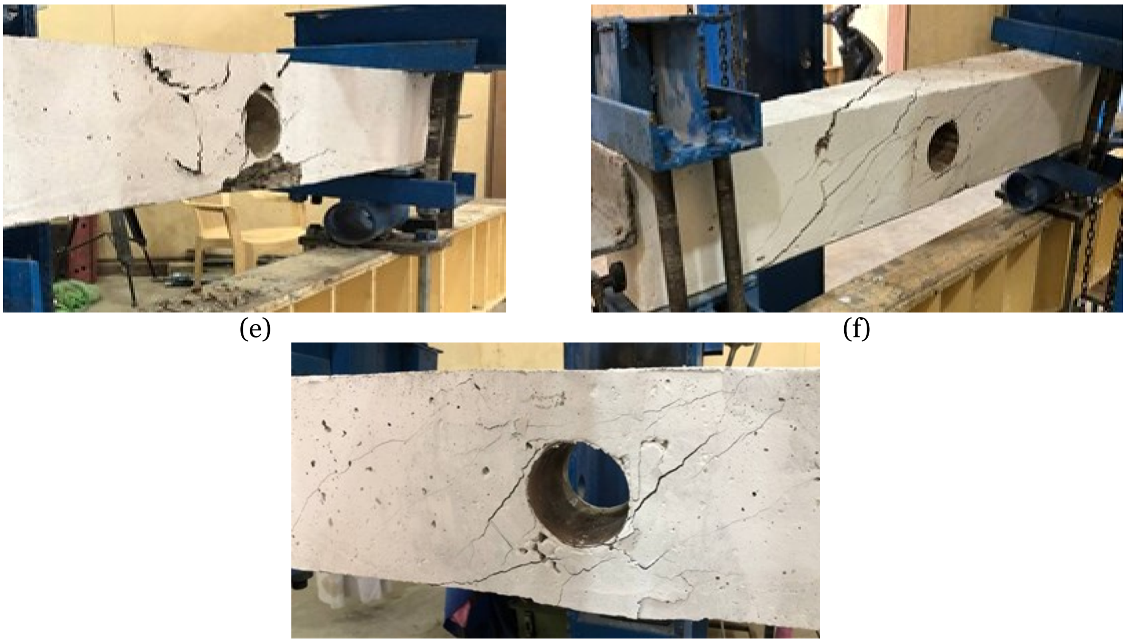


Fig. 11 Failure Mode and Crack Pattern for Small Opening Specimens: (a) CB, (b) P75 (c) S2-45, (d) S2-90, (e) S3-45, (f) S3-90, (g) S4-45, and (h) S4-90.





(e) (f)

(g)

Fig. 12 Failure Mode and Crack Pattern for Small Opening: a) P100, b) L2-45, c) L2-90, d) L3-45, e) L3-90, f) L4-45, and g) SL4-90.

4.2.5.Twisting Angles

Ductility is defined as the ratio between the maximum twisting angle resulting from the ultimate torque and the maximum twisting angle resulting from the first cracking load [6]. Table 11 shows all specimens' highest twisting angle at the start of cracking, ultimate torque, and ductility value. Figure 13 shows that increasing the thickness of steel pipe with a 90° orientation for large openings produced a notable improvement in ductility compared to the other specimen and a 0.5 percent increase in ultimate torque capacity. On the other hand, it can be seen that ultimate torque capacity was reduced by 18 %, and ductility increased by about 57% for beam S2-45 compared with CB.

Table 11 Results of the Twisting Angle at Cracking and Ultimate Torque.

Specimen	Twisting angle at cracking torque (rad.)	Twisting angle at Ultimate torque, θ_u (rad.)	Ductility (θ_u/ θ_{cr})	%
CB	0.009067	0.0648	7.15	---
P75	0.006133	0.068	11.09	35
P100	0.01307	0.0623	4.7	-34
S2-45	0.005733	0.096	16.75	57
S2-90	0.0064	0.092	14.84	51
L2-45	0.00907	0.1	11.03	35
L2-90	0.0044	0.0455	10.34	31
S3-45	0.00787	0.050667	6.44	-11
S3-90	0.00786	0.061333	7.8	8
L3-45	0.006133	0.05133	8.37	15
L3-90	0.008267	0.0872	10.55	32
S4-45	0.0128	0.07333	5.73	-25
S4-90	0.007867	0.062	7.88	9
L4-45	0.009067	0.108533	11.95	40
L4-90	0.005867	0.104667	17.84	60

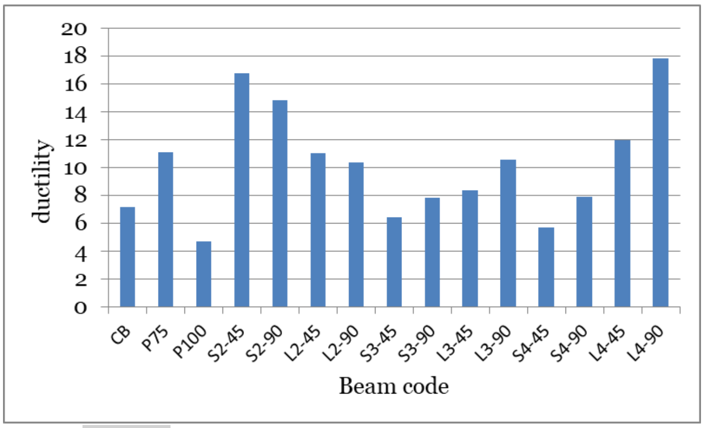


Fig. 13 Ductility Values for All Tested Beams.

4.2.6.Toughness

Toughness is an important mechanical property as it indicates the specimen's resistance to fracture. The load-displacement curves for the beams were depicted in Fig. 14 to identify the cracking load (T_{cr}), ultimate load (T_{ult}), and failure load (T_f) stages. It is possible to comprehend better how the material responds at various phases of loading by dividing it into three separate sections, designated as Area I, Area II, and Area III. These areas are pre-cracking (Area I), cracked before achieving ultimate torque (Area II), and post-cracking (Area III) torsional toughness [23]. The torsional toughness of these three areas was computed and plotted in Fig. 15 by applying the toughness model introduced in Fig. 14 on Fig. 7. By investigating Fig. 15, the Area I torsional toughness for all beams was almost equal except P100, indicating the similar pre-cracking behavior. For opening size, Area III was almost 0.55 kN.m.rad, representing the toughness for beams BC, P75, and P100, indicating the post-cracking behavior. Additionally, the Area II for beam P100 was 0.165 kN.m.rad, exhibiting a 48.39% decrease compared to BC and P75, i.e., beams BC and P100 may be cracked before achieving ultimate torque. Based on the reductions in the Area II torsional toughness for small openings due to 3mm steel pipe thickness with 45° orientation and increase in Area III by 36.36%. While for large openings, due to the 2 mm steel pipe thickness with 90° orientation and increase Area III by 23.63%, improving the beams with steel pipe is warranted.

4.2.7.Stiffness

T is the applied torque, and θ is the resulting twisting angle. The torsional stiffness of a beam determines its resistance to twisting, with higher values indicating greater rigidity and less deformation under torque. The slope of the torque-twisting angle at the service stage ($0.65T_{ult}$) represented the initial stiffness [24],[25]. Stiffness at ultimate torque can also be determined from the ratio of ultimate torque to the twisting at this torque [26]. Fig. 16 shows rotational stiffness values for all tested beam specimens. Furthermore, calculating the initial stiffness (k) for the linear portion of the torque-twisting angle curve adds another dimension to our understanding of the material's performance. The inclined reinforcement with small openings increases the initial stiffness, unlike in large openings, and the reason is that the inclined reinforcement compensates for the decrease that occurs due to the loss of concrete in the opening. In addition, the four fixing parts, which are T letter-shaped and at an angle of 90, clearly contributed to the increase in the initial stiffness, which is evident in the small openings.

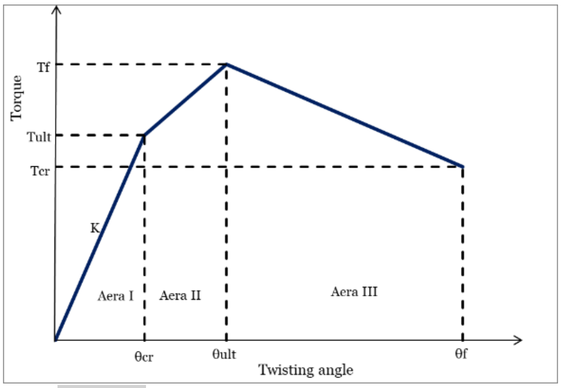


Fig. 14 Toughness Model (T=Torque, θ=Twisting Angle, ult=Ultimate, f=Failure, cr=Cracking, K=Initial Stiffness).

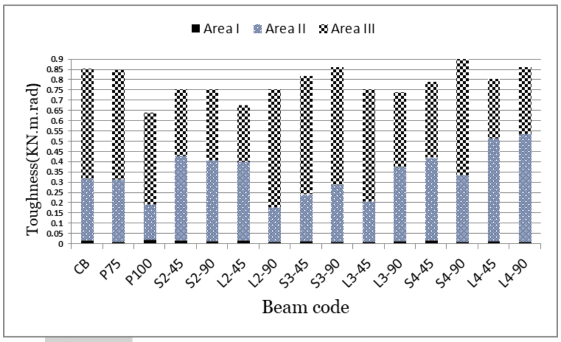


Fig. 15 Toughness Values for All Tested Beams.

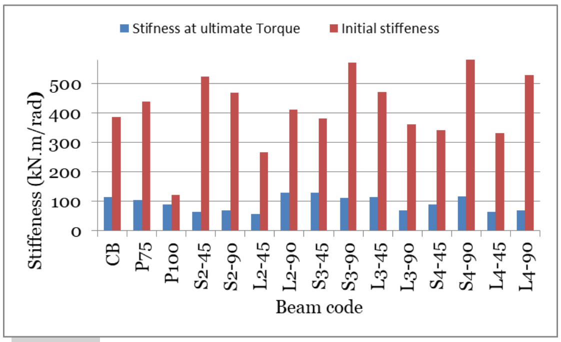


Fig. 16 Stiffness Values for All Tested Beams.

5.CONCLUSIONS

This study examined the influence of apertures at mid-span on the torsional performance of RC beams with two different steel pipe sizes and three different steel pipe thicknesses together with orientation. The following findings can be made from the experimental research on the torsional performance of RC beams:

- Using diagonal reinforcement insignificantly influenced torsional behavior in tiny openings. On the other hand, the diagonal reinforcement did not cover up for the large beam opening's decreased torsional strength.
- Using a steel pipe of 4mm thickness (1.0 of the stirrups diameter) was suitable to indemnify the absence of concrete in the opening and the diagonal reinforcement for both sizes of openings.

- The two orientations of steel pipes (45° and 90°) gave approximately the same ultimate torsional loads.
- Using a steel pipe of a thickness greater than or equal to 3mm (0.75 of the stirrup's diameter) prevents internal deformation of the opening pipe, providing more protection for this region.
- The toughness and initial stiffness of beams with small openings and beams with a pipe thickness of 4mm (1.0 of the stirrups diameter) are approximately the same.

ACKNOWLEDGEMENTS
The authors are grateful for the financial support given to this research by the Civil Engineering Department, College of Engineering, Babylon University.

REFERENCES

[1] Mansur MA, Ting SK, Lee S. **Torsion Tests of R/C Beams with Large Openings.** *Engineering Structures* 1983; **5**: 1780-1791.

[2] Amiri S, Masoudnin R. **Investigation of the Opening Effect on the Behavior of Concrete Beam Without Additional Reinforcement in Opening Region Using FEM Method.** *Australian Journal of Basic and Applied Sciences* 2011; **5**(5): 617-627.

[3] Ahmed A, Fayyadh M, Naganathan S, Nasharuddin K. **Reinforced Concrete Beams with Openings: A State of the Art Review.** *Materials and Design* 2012; **40**: 90-102.

[4] Alamli AS, Mehdi HA, Ahmed RH. **Torsional Behavior of Reacted Power Concrete T-Beams with Web Openings.** *Journal of Engineering and Sustainable Development* 2017; **21**(3): 72-86.

[5] Jithinbose KJ, Thomas J, Parappattu NB. **Effect of Openings in Beams - A Review.** *International Journal of Innovative Research in Advanced Engineering* 2016; **3**(9): 1-12.

[6] Abdo T, Mabrouk R. **Effect of Web Opening on the Structural Behavior of RC Beams Subjected to Pure Torsion.** *International Conference on Advances in Sustainable Construction Materials & Civil Engineering Systems 2017;* Sharjah, UAE: p. 1-10.

[7] Chiu HJ, Fang IK, Young WT, Shiau JK. **Behavior of Reinforced Concrete Beams with Minimum Torsional Reinforcement.** *Engineering Structures* 2007; **29**: 2193-2205.

[8] Hassan RF, Al-Salim NH, Mohammed NS, Hussein HH. **Experimental Study and Theoretical Prediction on Torsional Strength with Different Steel Fiber Reinforced Concretes and Cross-Section Areas.** *Engineering Structures* 2022; **251**: 113559.

[9] Hassan RF, Jaber MH, Al-Salim NH, Hussein HH. **Experimental Research on Torsional Strength of Synthetic/Steel Fiber Reinforced Hollow Concrete Beam.** *Engineering Structures* 2020; **220**: 110948.

[10] Teixeira MM, Bernardo LFA. **Ductility of RC Beams under Torsion.** *Engineering Structures* 2018; **178**: 759-769.

[11] Ling JH, Tung HS, Sia HT. **Behavior of Reinforced Concrete Beams with Circular Transverse Openings under Static Load.** *Journal of Science and Engineering* 2020; **3**(1): 1-16.

[12] Abdulrahman MB, Al-Jaberi LA, Hasan SS. **The Effect of Opening Size and Location on the Performance of Reinforced Concrete T-Beams under Pure Torque.** *Tikrit Journal of Engineering Sciences* 2020; **27**(2): 46-53.

[13] Hekal GM, Ramadan BA, Meleka NN. **Behavior of RC Beams with Large Openings Subjected to Pure Torsion and Retrofitted by Steel or CFRP Plates.** *Engineering Research Journal* 2020; **43**(2): 127-138.

[14] Atea RS. **Torsional Behavior of Reinforced Concrete T-Beams Strengthened with CFRP Strips.** *Case Studies in Construction Materials* 2017; **7**: 110-127.

[15] Kandekar SB, Talikoti RS. **Torsional Behaviour of Reinforced Concrete Beam Wrapped with Aramid Fiber.** *Journal of King Saud University - Engineering Sciences* 2019; **31**: 340-344.

[16] Nageh NM, Khaled MH, Ahmed N, Islam MO. **Behavior of Reinforced Concrete Beams Strengthened by GFRP Composites Subjected to Combined Bending and Torsion - Experimental Study.** *Engineering Research Journal* 2021; **44**(3): 295-302.

[17] Jasim IK, Abdulrahman MB, Jomaah MM, Alsubari B, Abdulaali HS, Alqawzai

S. **Torsional Behavior of RC Beams with Transverse Openings Strengthened by Near Surface Mounted-Steel Wire Rope Subjected to Repeated Loading.** *Tikrit Journal of Engineering Sciences* 2022; **29**(4): 79-89.

[18] ACI Committee 318. **Building Code Requirements for Structural Concrete and Commentary.** ACI 318R-14, American Concrete Institute; 2014.

[19] Iraqi Specification Standards. **Portland Cement.** IQS No. 5, Central Agency for Standardization and Quality Control; 1984.

[20] Iraqi Specification Standards. **Natural Sources for Gravel That Is Used in Concrete and Construction.** No. 45; 1984.

[21] ASTM International. **Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement.** ASTM A615/A615M-16; 2016.

[22] British Standards Institution. **Method for Determination of Compressive Strength of Concrete Cubes.** BS 1881-116; 1989.

[23] Mohammed NS, Hamza BA, Al-Shareef NH, Hussein HH. **Structural Behavior of Reinforced Concrete Slabs Containing Fine Waste Aggregates of Polyvinyl Chloride.** *Buildings* 2021; **11**: 26, (1-20).

[24] Al-Quraishy QAH. **Experimental and Theoretical Investigations for Behavior of Precast Concrete Girder.** *Journal of Engineering* 2012; **18**(5): 621-638.

[25] Al-Khafhji AGA, Al-Mamoori AHN, Abathar MAA. **Improvement of Flexural Strength of Precast Concrete Spliced Girder Using Reactive Powder Concrete in Splice Region.** *Structures* 2017; **14**: 197-208.

[26] Qiu M, Shao X, Yan B, Zhu Y, Chen Y. **Flexural Behavior of UHPC Joints for Precast UHPC Deck Slabs.** *Engineering Structures* 2022; **251**: 113422.