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TORSION PLUS BENDING AND SHEAR ON REINFORCED CONCRETE BEAMS

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Abstract: This paper is relevant with reinforced concrete beams subjected to combined torsional moments, bending moments and its comitant shear forces. Six identical beams in its dimensions and reinforcement, but different in the external loading setup were tested. The loading setup was applied in a manner depending on gradual ratio of bending moment to torsional moment; thereby, two beams were references to the other four ones. Experimental results revealed that, the loading setup is considerably effective factor on the structural behavior of the reinforced concrete beam. So that, through the loading setup, the presence of torsional moment leads to enhance the resistance of the beam over than 200% against combined loads than pure bending moment or torsional moment only. Also, the loading setup is capable of restoring the stiffness, maintaining the flexure mode of failure and raising the design safety factor for combined loaded reinforced concrete beams subjected to combined torsional moments, bending moments and shear forces.

Keywords: *beam, torsion, bending moment, shear, concrete, loading setup*

اللي بالإضافة إلى الانحناء والقص على الأعتاب الخرسانية المسلحة

الخلاصة: يتعلق هذا البحث بالأعتاب الخرسانية المسلحة المعرضة إلى اختلاط عزوم اللي، عزوم الانحناء وما يرافقها من قوى القص. تتألف نماذج البحث من ستة أعتاب متماثلة من حيث الأبعاد والتسليح، ولكنها مختلفة من حيث طريقة تحميلها الخارجي. تم تسليط الأحمال وفق أسلوب يعتمد على نسبة متدرجة من عزم الانحناء إلى عزم اللي؛ وبذلك كان هناك اثنان من الأعتاب تمثل مراجع مقارنة للأعتاب الأربعة الأخرى.أظهرت النتائج العملية أن أسلوب التحميل يمثل عامل مؤثر على السلوك الإنشائي للعتبة الخرسانية المسلحة. ومن ذلك أن أسلوب التحميل يجعل من وجود عزم اللي يؤدي إلى تعزيز مقاومة العتبة فوق ما يزيد عن ٢٠٠% أمام الأحمال المركبة عن مقاومتها لعزم الانحناء الصرف أو عزم الالتواء الصرف كل على حدة. وإلى جانب ذلك فإن كيفية التحميل قادرة على استعادة المتانة، الحفاظ على نمط فشل انثناء وزيادة معامل الأمان التصميمي للأعتاب الخرسانية المسلحة مركبة التحميل بتعريضها إلى إجهادات مركبة من عزوم اللي، عزوم الانحناء وقوى القص.

1. Introduction

It is agreed that, loading on reinforced concrete beams, especially spandrel one, is mainly combined of bending moment and shear force as well minor torsional moment.

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Despite bending moment is always decisive for alike combination of loading [1-3], however, load points of action and positions need to be observed its effects to assurance corresponded structure's performance and efficiency under a certain distribution of loading. Many researchers investigated beams subjected to pure torsion only [4,5] or combined torsion, bending and shear force [3, 6 and 7] through external point loads acting with eccentricity to the beam axis at or near its supporting zones. Whilst, another researchers [2, 8 and 9] conducted their papers to investigate beams behaviors under combined torsion, bending and shear force produced by eccentric load in the beam middle zone.

Almost of previous researches indicated decrease in strength and stiffness of beams tested under combined shear and bending stresses propagated from eccentric loading. Some researchers determined ratios of bending moment/torsional moment (λ) in which bending moment can be dominant on the beam structural behavior and failure mode. The ratio of dominant bending moment via precede researches is ($\lambda \geq 2.5$) [3], ($\lambda \geq 2.0$) [1] and ($\lambda > 1.0$) [6] where beams configurations and test setup were different in each research respectively.

Recently, strengthening of structures is become more intended and focused due to many professional, environmental and economic considerations. Thereby, strengthening of concrete structure can be achieved by; increasing its cross-sectional area with comitant transverse reinforcement, using externally bonded steel plates or post-tensioning the structure to apply axial load [10]. Fiber reinforced polymer (FRP) carbon [11-13], glass [14, 15] and composites [16] bonded externally or embedded internally [17] in modern options used successfully for strengthening beams subjected to combined loading. Additionally, steel fibers (SF) are another strengthening option for beams suffering from high tensile stresses under combined loading [4, 5 and 7].

2. Objective

The present paper aims to study the effects of torsional load presence in the structural behavior of reinforced concrete beams subjected to combined bending and shear stresses firstly, and seeks about how loading can be distributed to attain more efficiency for the beams without using any further strengthening technique secondly.

3. Experimental Work

3.1. Testing Program

In this paper, loading is arranged to apply a concentric point(s) load in beam middle zone as well as two eccentric points load at the beam supports (ends). So, four beam specimens have gradual descended values of (λ) were tested under torsion moment plus bending moment and shear. Another two beam specimens; one under pure bending moment and the other under pure torsion moment, were tested in a manner to be references specimens for the other four ones.

3.2. Specimens Details

The total number of specimens is six reinforced concrete beams and two of them are references. The first reference beam (B1) was tested under central point load only to be subjected to moments producing bending without torsion, so the (λ) of the beam is infinity (∞). The opposite reference beam (B6) was subjected to pure torsion and tested under eccentric two halves load at the ends of the beam (support zones) to make the beam free of bending moments with (λ) value equals zero (0). The rest four beam specimens are the main specimens of the study and they were tested under combined bending and torsional moment as well of course their comitant shear stresses. Loading setup of the main beams is similar to beam specimen (B6) for producing torsional moments; however, bending moments were produced by additional point(s) load in the beam midspan to achieve the study objectives. The external loading setup for the specimens is shown in Fig. 1 while all these specimens are identical in dimension and reinforcement, as shown in Fig. 2. All the tested beams were cast with normal strength concrete and dimensions of 100 x 200 x 2200 mm. The dimensions, longitudinal reinforcement and transverse reinforcement of the beams are selected to be within the limitations of ACI Code 318M-14 [18] to ensure the flexure mode of failure.

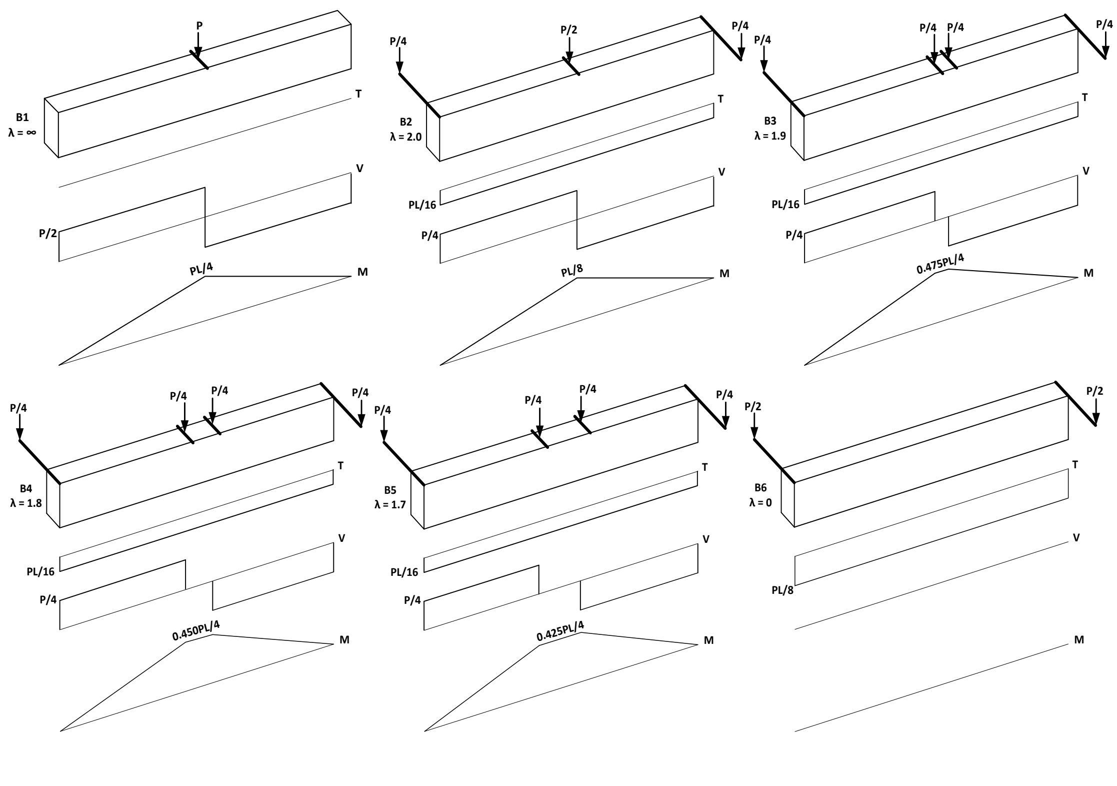


Figure 1: Loading setup for specimens

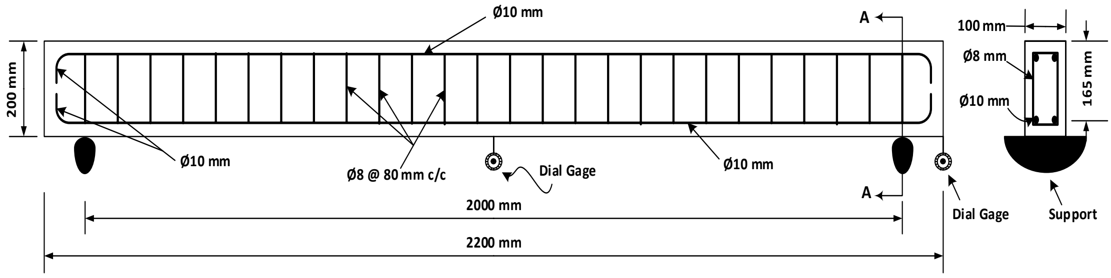


Figure 2: Reinforcement details

3.3. Materials Properties

Description and properties of the used materials are listed in Table 1. The used materials are compiled with the Iraqi specifications. However, tap water was used for mixing the concrete. The mix proportions to compose normal strength concrete for the tested beams are listed in Table 2. It may be noted that, tap water was used for mixing and curing of concrete samples without any admixture or treatment agents.

Table 1: Properties of materials

Material	*Description*	Iraqi Specification
Cement	Bazian Ordinary Portland Cement Type(I)	No. 5 / 1984 [19]
Sand	Al-Ukhaider natural sand with maximum size of 4.75 mm and fineness modulus of 2.60	No. 45 / 1984 [20]
Gravel	AL–Nibae crushed gravel with maximum size of 14mm and bulk specific gravity of 2.64	
Ø10 mm Bars	Deformed steel bars having strengths of yield (f_y) /ultimate (f_u) = 484/719 MPa	No. 2091 / 1999 [21]
Ø8 mm Bars	Deformed steel bars having strengths of yield (f_y) /ultimate (f_u) = 430/602 MPa	

Table 2: Mix Proportion

Cement (kg/m^3)	*Sand (kg/m^3)*	*Gravel (kg/m^3)*	Water (L/m^3)
450	635	1085	180

3.4. Compressive Strength of Concrete

The compressive strength of hardened concrete was carried out by using 150 x 300 mm cylinders according to ASTM C39/C39M-16 [22]. The average cylinder compressive strength (f'_c) was 31.7 MPa.

3.5. Modulus of Rupture of Concrete

The modulus of rupture tests of hardened concrete was carried out by using 100 x 100 x 500 mm prisms according to ASTM [23]. The average modulus of rupture (f_r) was 4.4 MPa.

3.6. Instrumentations and Testing

All the beams were tested with clear span (L) of 2000 mm between supports and firstly colored by white paint to facilitate detection of cracks. One dial gage of 0.01 mm divisions and 50 mm capacity was positioned at the beam midspan to measure deflection when bending moment is a part of loading. Occasionally, in case of torsion loading presence, two dial gages of 0.002 mm divisions and 30 mm capacity were positioned at one end of the beam span to measure the vertical movements of the bottom fiber at the opposite corners of the beam end. So, the average of twisting angle can be calculated approximately through a simple method as shown in Fig. 3.c

Testing machine is a universal (MFL) type of 3000 kN maximum capacity; which shown in Fig. 3. Loading was applied with 5 kN gradual increment and continued up to failure. During test, midspan deflection and/or twisting angle were measured at each stage of load increase.

a: Testing machine b: Test setup c: Angle of twist measuring

Figure 3: Testing details

4. Results and Discussion

Test results in terms of ultimate load (P_u) and midspan deflection (Δ) are arranged in Table 3 and discussed more detailed under specific topics therein. The ultimate strength means the total applied loads on the tested beam at failure.

Table 3: Test Results

Beam Symbol	*M/T (λ)*	P_u *(kN)*	*Δ (mm)*	*ϕ (deg.)*	Failure Mode
B1	∞	25	1.94	0	Flexure
B2	2	35	3.42	3.45	Flexure
B3	1.9	52	4.83	5.35	Flexure
B4	1.8	60	5.81	6.29	Flexure
B5	1.7	73	7.85	6.65	Flexure-Shear
B6	0	35	0	4.80	Shear

4.1. Beam Strength

The recorded load, at any stage of test, is the total applied load from the hydraulic machine, so the strength of the tested beam is indicated by the ultimate applied load (P_u) at or closely near failure. In the present work, the four main beam specimens (B2-B5) exhibited increases in total strength exceeded its references beams (B1 and B6).

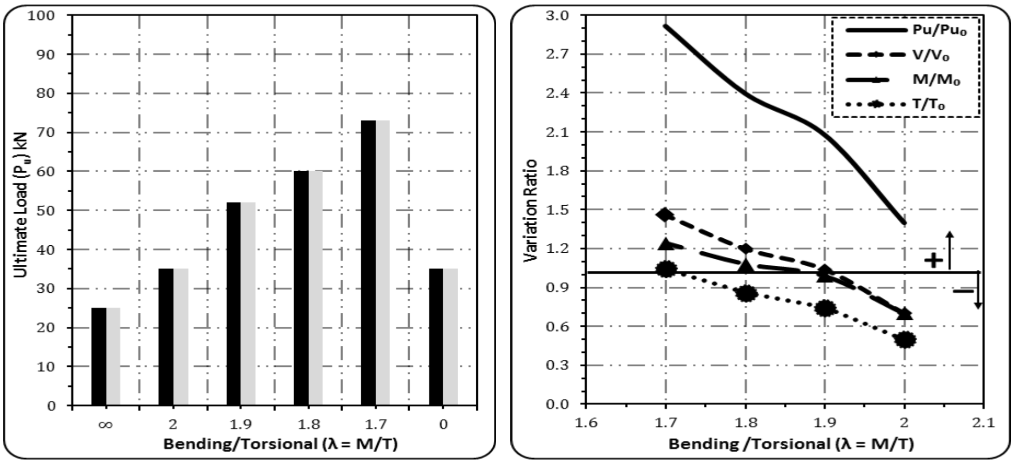
The strength of the specimens enhanced gradually, higher than references, to reach greater than 200% in beam specimen (B5) and this result revealed the loading setup high action in raising the beam capacity against combined bending and torsion to emphasize the conclusion of Ref [3]. In addition, the results indicated that for the combined loading; when the ratio of bending moment/torsional moment (λ) of the beam decreased, its strength will increase and even the rate of (λ) decrease was small the rate of strength increase was considerable. The enhancement of beams strengths is graphed in Fig. 4.a.

The original ultimate strength capacity came from pure type of loading on the reference beams; therefore, (T_0) is the torsional ultimate strength of beam specimen (B6) while (M_0) plus (V_0) are the bending and shear components of the ultimate strength of beam specimen (B1) respectively. While for the main beams, the ultimate load which represents the beam strength is analyzed into torsional, bending and shear components. Table 4 contains the components of the ultimate strength of each tested beam which are collected to establish the interaction diagrams and other curves.

Table 4: Ultimate load components

M/T (λ)	*T (kN.m)*	*T_O (kN.m)*	*T/T_O*	*M (kN.m)*	*M_O (kN.m)*	*M/M_O*	*V (kN)*	*V_O (kN)*	V/V_0
∞	0	8.75	0	12.50	12.50	1.0	12.50	12.50	1.0
2	4.38		0.5	8.75		0.70	8.75		0.70
1.9	6.50		0.74	12.35		0.99	13.0		1.04
1.8	7.50		0.86	13.50		1.08	15.0		1.20
1.7	9.13		1.04	15.51		1.24	18.25		1.46
0	8.75		1.0	0		0	0		0

In this paper, the loading setup was directional agent to control (λ) values. When the concentric points load more diverge, the ratio of torsional moment increases and leads to decrease (λ) value. It can be noticed that, the decreasing of (λ) leads to enhance the total strength of the beam combined loading. However, other components of strength get improvement due to decreased (λ) and with (λ = 1.7) the beam is capable to resist torsion, bending and shear well than when it in case of resisting pure flexural or torsional only. Increasing the moment ratio to be (λ = 2) means the combined loaded beam failure in torsion, bending or shear less than its capacity when it is subjected to pure torsion on bending moment but with higher resultant strength in comparison with its pure bending or torsion reference and that is clear in Fig. 4.b.



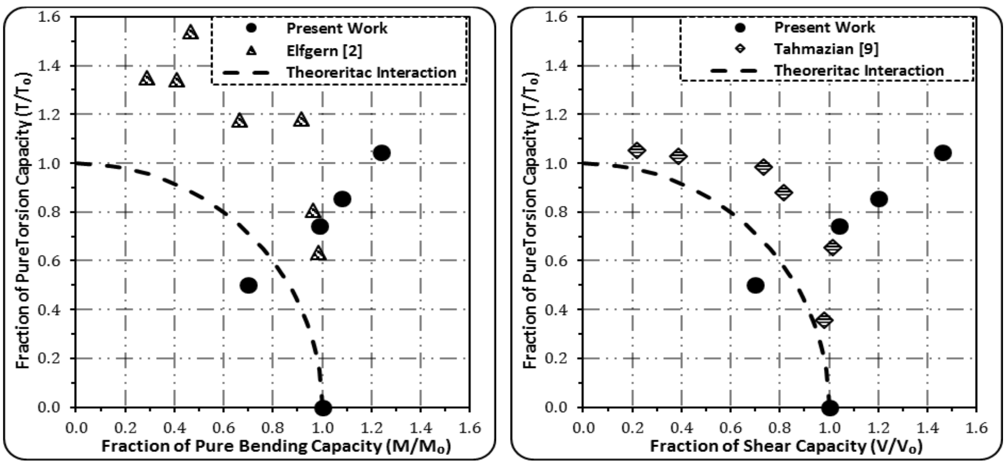
a: Total strength b: Components strengths

Figure 4: Strength of the tested beams

4.2. Interaction Diagrams

The interaction diagrams are very important tool for some design procedures. So, establishing these diagrams through experimental results leads to check its confidence and safety factors. In the present work, the main interaction diagrams for beam strength against combined bending and Torsional moments are illustrated in comparison with theoretical limits and other researches results.

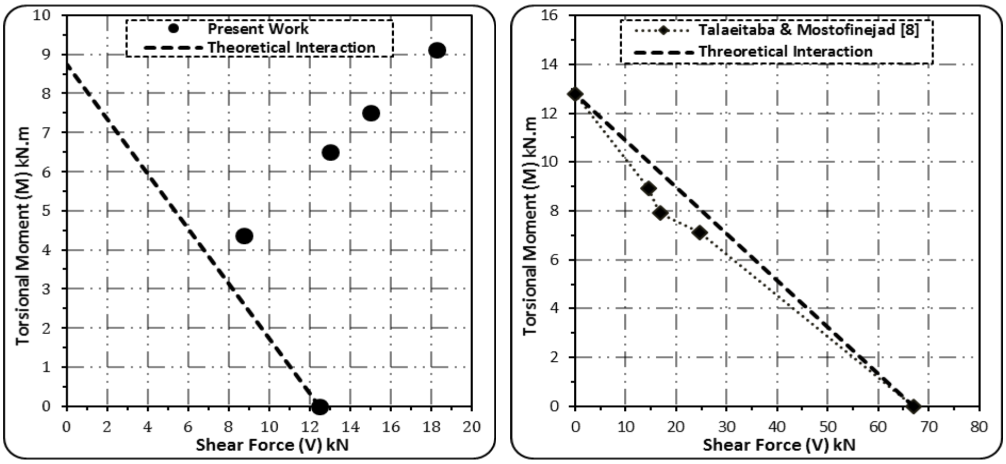
Torsional capacity is interactional in non-dimensional diagrams with flexural capacity in Fig. 5.a and with shear capacity in Fig. 5.b. For the two present experimental diagrams, only one beam of combined specimens (B2) where (λ = 2) has strength less than the theoretical curves, however, by increasing the amount of torsion to decrease the value of (λ), the strength of beam become greater than both the theoretical curves and the experimental results of [2, 9] researches. It is clear that the trend of the present results dispersion depends on the loading setup, so that the test configurations of [2, 9] are illustrated in Figs. 7.a and 7.b.



a: Torsion vis. bending b: Torsion vis. shear

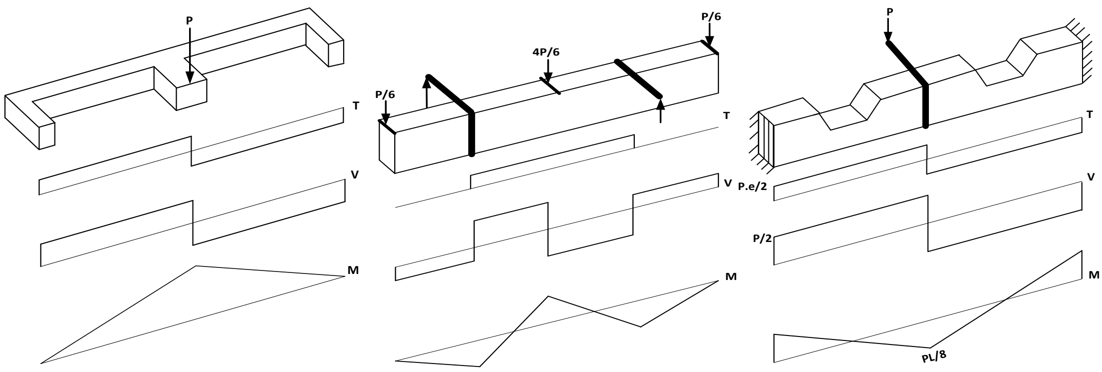
Figure 5: Non-dimensional interaction diagrams of the tested beams compared to others

Torsional capacity is also interactional with shear capacity in Fig. 6.a to compare it with the experimental results of [8] in Fig. 6.b where linear theoretical interaction is concluded. The present results did not coincide with the theoretical interaction and dispersed orthogonally with this line to be always above it. The non-conformity between the theoretical line and present results is because of the loading setup different to that of [8] shown in Fig. 7.c. Since the achieved results, the loading setup is very effective on the interaction diagrams of reinforced concrete beams subjected to combined torsion, bending and shear.



a: The present results b: Ref [8] results

Figure 6: Torsion-shear interaction diagrams of the tested beams compared to others

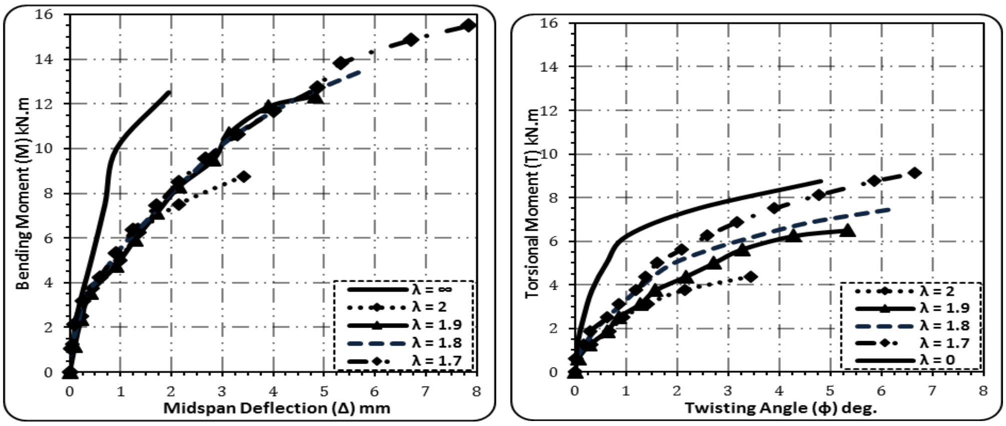


a: Ref [2] setup b: Ref [9] setup c: Ref [8] setup

Figure 7: Loading setup of other referred researches

4.3. Flexural and Torsional Stiffness

Experimental observing of a beam stiffness depended on its response in terms of deflection and twisting angle values under the applied load, therefore, bending moment-midspan deflection curve is illustrated to clarify the flexural stiffness and also torsional moment-twisting angle curve is illustrated to clarify the torsional stiffness of the tested beams as in Fig. 8.



a: Flexural stiffness b: Torsional stiffness

Figure 8: Stiffness of the tested beams

Generally, the tested beams exhibited similar behavior. However, Fig. 8.a revealed that the flexural stiffness of the tested beams is greater than its torsional stiffness in Fig. 8.b and that is rational because elastic modulus of any beam is greater than its shearing modulus. It is clear that when the beam is subjected to pure flexure ($\lambda = \infty$) or pure torsion ($\lambda = 0$) only its stiffness will be better than one when it is subjected to combined flexure and torsion and this result complies with Ref [1]. Another achieved result is increasing the ratio of torsion to the bending moment leads to improve the beam stiffness in both flexural and torsional, so the value of (λ) decreased gradually (2 – 1.7) the corresponding deflections and twisting angles also decreased during all stages of testing. It can be concluded that the loading setup is considerably effective in the beam stiffness.

4.4. Failure Mode

At early stage of test, the beams were deformed by rotations and deflections but without cracking, after that cracking appeared and propagated gradually. Near failure, the cracks developed rapidly up to loading from the testing machine dropped. Pure flexural beam ($\lambda = \infty$) failed by vertical crack extended vertically in the middle of the beam while pure torsional beam ($\lambda = 0$) failed by diagonal cracks extended along the entire beam. For the beam specimens subjected to combined torsion and bending, diagonal cracks extended along the beam but the failure achieved by vertical crack in the middle of the beam. Especially for beam specimen (B5) of ($\lambda = 1.7$) where the rate of torsion is higher than the others, failure achieved in the middle of the beam but with crushed concrete around the diagonal cracks in form of shear-compression failure. The failure mode revealed that, for beams subjected to combined to bending and torsional moments, the loading setup is effective in the failure mode and when ($\lambda \geq 1.7$) the bending moment is dominant. Cracking of the tested beams at failure is photographed in Fig. 9.

Figure 9: Failure of the tested beams

5. Conclusions

The experimental results of the present work revealed that, the loading setup is an effective parameter on the structural behavior of reinforced concrete beam subjected to torsion moment in addition to bending and shear stresses.

Diverging the concentric points load in the beam middle zone in order to decrease bending moment/torsional moment (λ) value, lead to enhance the beam resistance to combined torsion, bending and shear over than 200%.

The experimental results dispersion trends around theoretical curves in the interaction diagrams of reinforced concrete beams subjected to combined torsion, bending and shear are considerably dependent on loading setup.

Despite the stiffness of beam subjected to pure flexure or pure torsion only is better than one when it is subjected to combined flexure and torsion, decreasing (λ) value decreases deflections and twisting angles. So, loss of beam stiffness can be restored.

In the present study, the loading setup revealed that the structural behavior of the reinforced concrete beam can be improved by increasing the torsional moment ratio up to ($\lambda \geq 1.7$) where the bending moment is dominant. Further work with increased torsional moment to attain ($\lambda < 1.7$) is suggested to investigate the structural behavior and especially failure warranty of combined loaded reinforced concrete beams

Abbreviations

f'_c	Cylindrical Compressive strength of concrete
f_r	Tensile strength of concrete.
f_y	Yielding stress of reinforcing steel
f_u	Ultimate strength of reinforcing steel
P_u	Resultant strength of beam-specimen
P_{uo}	Resultant strength of reference beam
V	Shear strength of beam-specimen
V_0	Shear strength of reference beam

M Flexural strength of beam-specimen
M_0 Flexural strength of reference beam
T Torsional strength of beam-specimen
T_0 Torsional strength of reference beam
λ Ratio of applied bending moment / torsional moment
Δ Midspan deflection due to bending moment
Φ Angle of twist due to torsional moment at the beam ends
Ø Diameter of reinforcing steel

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