Al-Azhar University Civil Engineering Research Magazine (CERM)
Vol. (41) No. (2) April, 2019

INVESTIGATION ON COMPATIBILITY TORSION OF CONCRETE FLOOR SLAB

B.M. SEDKY[a], A.A. Abd el-rahman[b,*], O. El-nesr[b,*], A. Beih[b]
[a] *Structural Engineering Department, Faculty of Engineering, South Valley University, Egypt*
[b] *Structural Engineering Department, Faculty of Engineering, Ain Shams University, Egypt*

الملخص العربى:
يهدف هذا البحث الى دراسة تأثير عزوم اللّى التوافقى فى البلاطات الخرسانية ومدى تأثره عند اختلاف نسبة التسليح عند نقطة الأتصال بين كمرتين.
تم دراسة عدد اثنين عينة من الخرسانة الملسحة مكونة من كمرتين متقاطعتين على شكل حرف (T) وتم تثبيت الكمرة الرئيسية من طرفيها و التأثير بحمل استاتيكى فى منتصف الكمرة الثانوية حتى الأنهيار وتم تغيير نسبة التسليح العلوى عند تقاطع الكمرتين بحيث يكون الأتصال عند التقاطع فى عينتين اتصال مفصلى (Hinged) وتم ايضا التغيير فى نسبة التسليح للكمرة الرئيسية بحيث تم تسليحها لمقاومة عزوم اللّى التوافقى فى عينة وذلك عن طريق زيادة الكانات بينما فى العينة الأخري لم يتم الأخذ فى الأعتبار تسليح الكمرة الرئيسية لمقاومة عزوم اللّى التوافقى ، مقاومة الخرسانة للكمرتين المتقاطعتين ثابتة للعينات 25 نيوتن/مم^2 والبحر الفعال للكمرة الرئيسية 2.70 م،البحر الفعال للكمرة الثانوية 3.50م وكلاهما ثابت للعينات ولكل عينة نفس الأبعاد تم تعيين حمل الأنهيار للعينتين، الترخيم، الدوران، رد الفعل عند ركيزة المثبتة فى نهاية الكمرة الثانوية، والأنفعال بالحديد الرئيسى للكمرتين الرئيسية والثانوية وكذلك الأنفعال بالكانات وتم عمل تحليل بطريقة العناصر المحددة للتحقق من النتائج التى تم الحصول عليها معمليا. وبصفة عامة، كان هناك توافق كبير بين كل من النتائج المعملية والعددية. وتم عمل استنتاجات ومقترحات من هذا البحث.

ABSTRACT

Many structural elements such as eccentrically loaded bridge girders, beams curved in plan, and spandrel beams in buildings are subjected to significant torsional moments. Such members are subjected to twisting about its longitudinal axial, known as torsion, in addition to the shearing force and bending moment, hence the external loads act far away from the vertical plane of bending. To design such members, it is essential to recognize whether the torsional moment is required to maintain equilibrium or compatibility. Torsional moments encountered in reinforced concrete buildings are of compatibility torsion, and their calculations poses a challenge. Once the spandrel beam cracks in torsion, its torsional stiffness reduces substantially. The reduction causes a significant redistribution of torque to the framing element. The presented thesis introduces an experimental and analytical study in order to investigate the compatibility torsion of spandrel beams taking into consideration the following torsional reinforcement for main beam (spandrel beam), fixation intersection, and reinforcement ratio for negative stress.

KEYWORDS

Compatibility, Torsion, Spandrel, Rotation, Torsional reinforcement, RC, T-shaped frame, Grid slabs.

1 INTRODUCTION

The ACI Code provides a so-called compatibility torsion for the design of spandrel beams in a statically indeterminate structure, when the torsional moment in the spandrel beam can be redistributed to other adjoining members after the formation of plastic hinges. Utilizing the limit design concept, this torsional plastic hinge can maintain a much smaller moment than that calculated by elastic analysis, thus resulting in a costeffective, and yet very simple, design. This compatibility torsion, will now be studied in a more detailed and systematic manner.

In this research, the redistribution of moment from a spandrel beam after torsional cracking to the adjoining floor systems will be illustrated by a three-dimensional structural frame, T-shaped frame. The portion of the frame consists of spandrel beam intersected of floor beam in its mid span. When a concentrated load (P) is applied on mid span of floor beam, it will produce a rotation at the ends that in turn induces a torsional moment in the spandrel beams.

Study was implemented depending mainly on static analysis and design regulations of the Egyptian code for the design & construction of reinforced concrete buildings (ECP). In recent years the evolution of computer technology has advanced to the stage where the finite element method (through codes such as 'SAP2000') can realistically be used to model full-scale buildings and subject them to a variety of loads, including seismic.

2 EXPERIMENTAL PROGRAM

The experimental work of the present study consists of testing two T-shaped reinforced concrete frames.

2.1 Test Specimens

This research consists of one group (G1), group consists of two specimens, G1 consists of SP1 and SP2. Intersection joint of G1 is hinged but that for SP2 taking into consideration torsional reinforcement of spandrel beam by means stirrups, on contrast no torsional reinforcement for spandrel beam of SP1. All specimens have the same dimensions, spans, and compressive strength. Group (G1) has a two intersected beams formed T-shaped specimen, (main beam) has 2.70 m effective span, 200 mm width and 350 mm depth, intersected in its mid span by (secondary beam) has 3.50 m effective span, 150 mm width and 300 mm depth. Max load at midpoint of secondary beam according to positive moment = 5.45 ton for SP1&SP2, max load at intersection of secondary beam according to negative moment = 2.98 ton for SP1&SP2, max load at midpoint of main beam according to positive moment = 12.07 ton for specimens, max torsional load of main beam according to torsional moment = 2.06 and 6.61 for SP1 and SP2 respectively. All specimens were provided with the same identical concrete dimensions, as shown in **Fig. (1)** that shows the geometry of the tested specimen.

Table (1): *Description of the T-shaped test specimens*

Groups	Group G1	
Specimens	SP1	SP2
RFT (+ve) Main beam	4Ø16	4Ø16
RFT (-ve) Main beam	2Ø10	2Ø10
RFT of stirrups Main beam	5Ø6/m'	9Ø8/m'
Value of (-ve) moment	PL/16 (Hinged Joint)	PL/16 (Hinged Joint)
RFT (+ve) secondary beam	5Ø12	5Ø12
RFT (-ve) Secondary beam	2Ø8	2Ø8
RFT of stirrups secondary beam	5Ø10/ m'	5Ø10/ m'

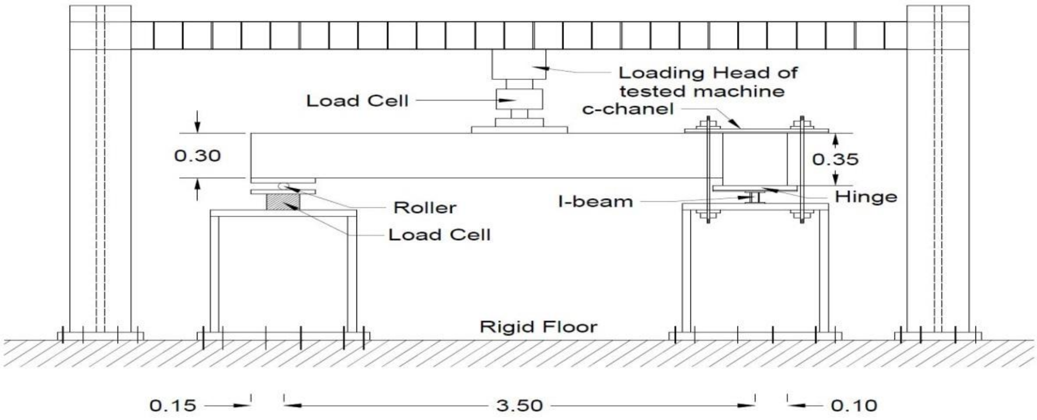


Fig. (1): Concrete Dimension and Steel Reinforcement of T-shaped Specimen

2.2 Equipment and Instruments:

The two specimens were tested in the RC laboratory of Ain Shams University. The specimens were tested using a hydraulic jack of 220 ton capacity that they were tested directly by applying a concentrated load at the mid span of the secondary beam for SP1 and SP2 and a load cell of 80 ton capacity is under free end of secondary beam to measure support reaction as shown in **Fig. (2)**. Before testing the specimens, a calibration was done for hydraulic jack by using a calibration ring in order to control the load at mid span of secondary beam during the tests. A hydraulic jack imposed the load at mid span of secondary beam, beam was loaded with a constant load of 5.00 kN load increments downwards at mid span of it, and main beam is torsionally fixed from two ends, also load cell is under the free end of secondary beam to measure reaction till failure.

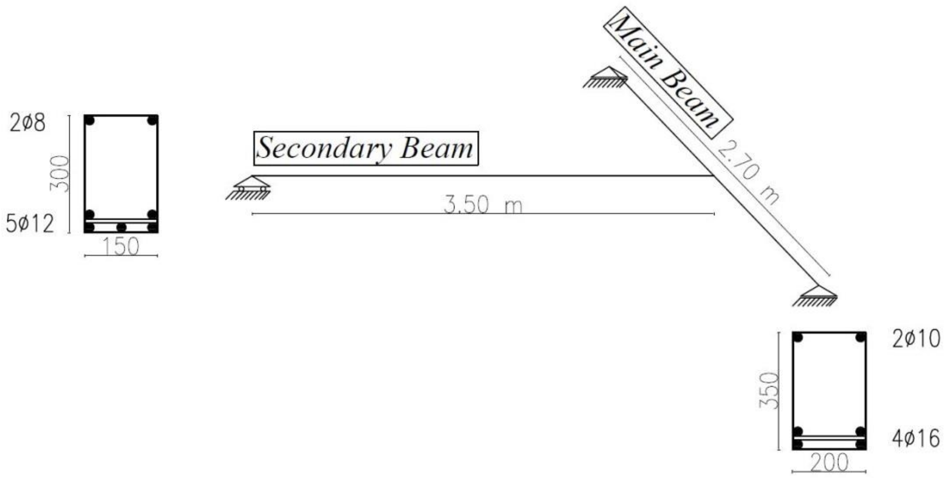


Fig. (2): *Testing Set-Up For all specimens (Side& Elevation views)*

2.2.1 Measuring devices:

Six linear variable displacement transducers (LVDT) with 120 mm range, two were used to measure the beam deflection at the mid span of main and secondary beams, two were used to measure rotation at intersection behind main beam, two at first main beam to ensure that main beam is torsionally fixed. The strains of steel bars were measured using electrical strain gauges with 120 ohm resistance fixed on the extreme tension regions, at mid span of main and secondary beam, at intersection for negative steel of secondary beam and at stirrups in max shear zones. These gauges were fixed on the steel bars before casting using special glue and covered with a water proofing material to protect them. Load cell with 80 ton capacity is under free end of secondary beam to measure reaction. The data acquisitions were used in the measurements of strains and deflection and corresponding acting load on tested specimen. **Fig. (3)** Show general arrangement for deflectometer and electrical strain gauges for all specimens.

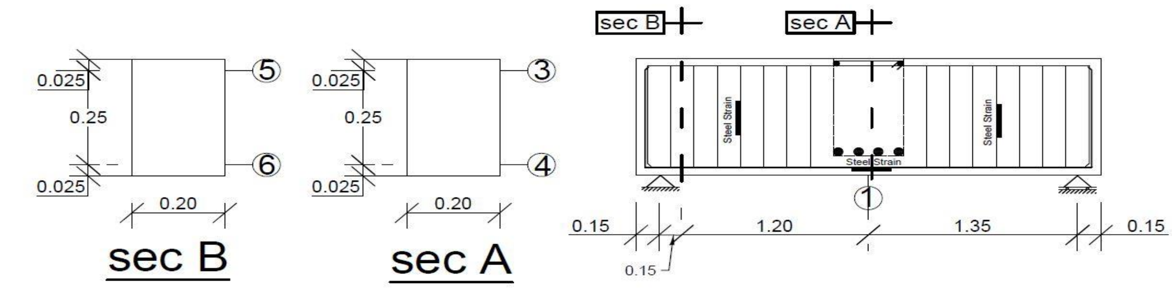


Fig. (3): *General Arrangement for Deflectometer and Electrical Strain Gauges (Main Beam)*

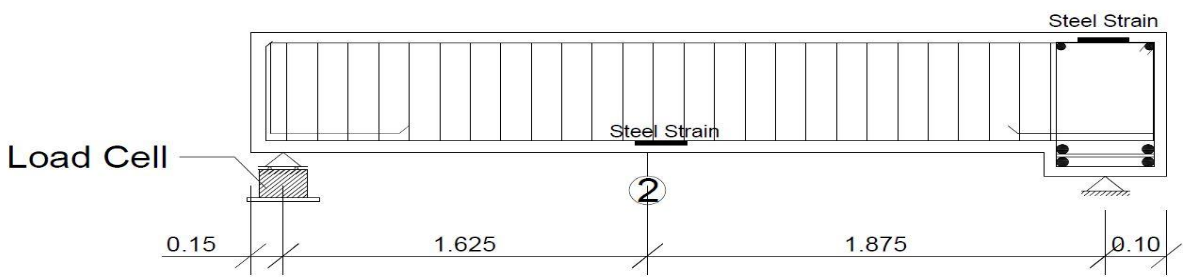


Fig. (3): *General Arrangement for Deflectometer and Electrical Strain Gauges (Secondary Beam)*

2.3 Test Procedure:

Groups G1 was tested using an incremental static loading procedure.
The specimens were loading statically from zero up to failure one loading cycle was applied using an incremental load of about 7-14% of the ultimate load was applied, till failure. In this respect, 5.00 kN load increments were used till cracking in order to get accurate measurements of the cracking load. Afterwards, the load increments were increased to 10.00 kN till failure was reached. At the end of each load increment, the load was held constant for a period of about 3 minutes, to allow measurements and

observations. All the readings of beam deflection, tension strain were recorded at all load stages using computer controlled data acquisition system. All the cracks lines were marked using marker pen. All the process took time at about 40 minutes for every specimen.

3 EXPERMENTAL RESULTS

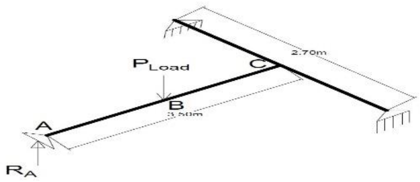
3.1 Crack Patterns, Cracking Loads and Failure Loads

For the first specimen (SP1), the first crack appeared at a load equal to 2.00 KN at mid span of secondary beam vertically at lower side under load head of tested machine. Approaching the failure load, the cracks spread inclined towards load head of tested machine.

For the second specimen (SP2), the first crack appeared at a load equal to 5.00 KN at mid span of secondary beam vertically at lower side under load head of tested machine. Approaching the failure load, the cracks spread inclined towards load head of tested machine, **Figs. (4)** show the general crack patterns for the tested T-shaped specimens. .

Table (2), shows the cracking load (P_{cr}) at which the first crack appeared, cracked ultimate moment at mid span of secondary beam (M_{Bcr}), cracked ultimate negative moment at intersection (M_{Ccr}), cracked torsional moment ($M_{TOR\ cr}$), the failure load (P_f), failure ultimate moment at mid span of secondary beam ($M_{B\ f}$), failure negative moment at intersection (M_{Cf}), and failure torsional moment ($M_{TOR\ f}$).

Table (2)*: Experimental Results of Cracking Load, Failure Load*

Groups	**Group G1**	
T-shaped Specimen	**SP1**	**SP2**
P_{cr} (KN)	2.00	5.00
M_{Bcr} (KN.m)	1.75	4.38
M_{Ccr} (KN.m)	0.44	1.09
$M_{TOR.cr}$ (KN.m)	0.22	0.545
P_f (KN)	53.01	60.54
$M_{B\ f}$ (KN.m)	46.38	52.97
$M_{C\ f}$ (KN.m)	11.59	13.24
$M_{TOR.f}$ (KN.m)	5.795	6.62
Failure Mode	Tension Failure	Tension Failure
Specimen Shape		

Figs. (4) General Crack Patterns of Tested T-shaped Specimens

From **table (2) and figures (4),** the following remarks could be concluded:
For the tested specimens, Investigation of the results reveals that the failure load of T-shaped specimen SP2 (60.54 KN) is more than failure load of SP1 (53.01 KN) that SP1&SP2 are hinged intersection, but main beam for SP2 is torsionally reinforced by means stirrups.

Regarding of T-shaped specimens failure loads of specimens SP1 and SP2 the experimental results indicates increasing of failure and cracking loads by taking into consideration torsion reinforcement for main beam and fixation of intersection is more effective than hinged one.

3.2 Load-deflection relationship of specimens

The experimental results of load-deflection curves at mid span of main and secondary beams for T-shaped specimens SP1 and SP2 were plotted as shown in **figure (5).**

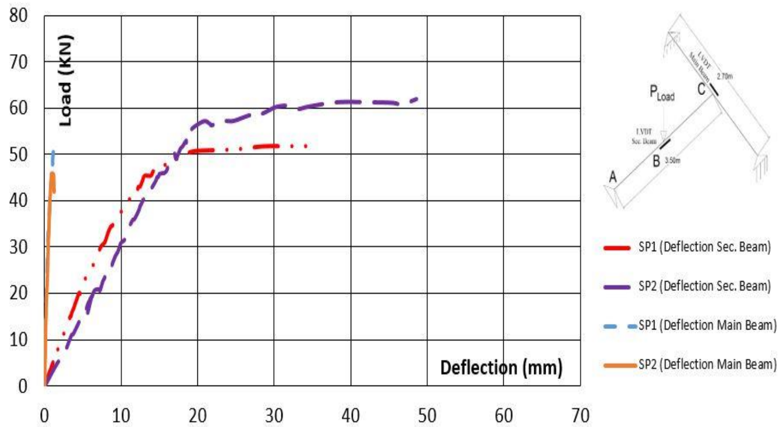


Figure (5) Experimental Results of Load – Deflection

Curves at mid span of Main& Secondary beam for (G1)

From **figure (5)**, the following remarks could be concluded:

For the tested specimens, the maximum mid span secondary beam deflections at failure load of specimens SP1& SP2 are 34.75 mm and 31.90 mm respectively, but at mid span main beam of the same specimens are 1.48 mm and 0.93 mm respectively. Figure (5), Group (G1) demonstrates that deflection at mid span secondary beam of SP2 decreases by 8.11% compared to SP1, but decreases by 37.16% for the same specimens at mid span main beam.

From these figures, it can be noted the effect of torsional reinforcement for main beam by means stirrups on secondary and main beam of T-shaped deflections that by taking into consideration torsional reinforcement for main (spandrel) beam at SP2 (9ø8\m') that increases load failure and decreases deflection for main and secondary beam compared to SP1 which has no torsional reinforcement for main beam (5ø6\m').

Finally, the load deflection curves of the tested frames are nearly linear at the early stages of loading, up to the yielding load. However, once the yielding occurs excessive cracks take place, and accordingly the deflections increase rapidly.

3.3 Rotation (Angle of twist)

3.3.1 Load-rotation (Angle of twist) relationship for specimens

The experimental results of load load-rotation curves for rotation (angle of twist) of main beam at intersection joint of models (SP1 and SP2) were plotted for the two tested specimens as shown in **figure (6).**

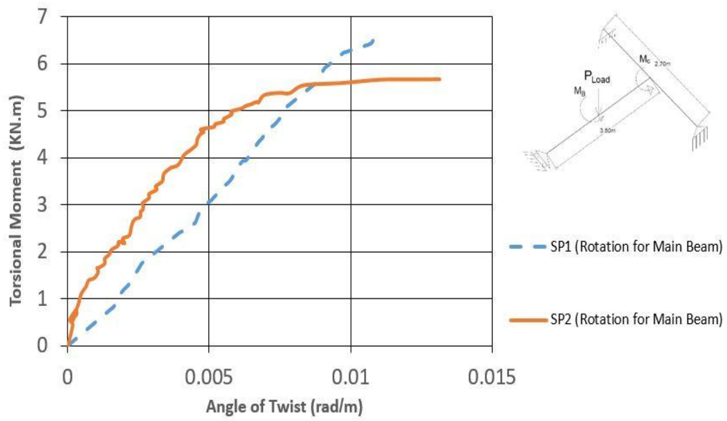


Figure (6) Experimental Results of Torsional Moment (Mt)-Angle of Twist (θ) Curves of Main Beam for (G1)

From **figure (6)** the following remarks could be concluded:

For the tested specimens, figure (6) Group (G1) indicates the effect of torsional reinforcement on load-rotation curves that its cleared that specimens behave in a reasonably elastic manner up to cracking. Before cracking the load-rotation curve is approximately linear. After cracking, the load-rotation curve reach a horizontal line, where the rotation increases under a constant load this confirm existence of moment redistribution. In other words, plastic hinges are formed in the spandrel beam after cracking.

3.4 Strains

3.4.1 Load-reinforcement strain relationship for specimens

The experimental results of load load-strain curves for the longitudinal reinforcement of the main and secondary beam of models (SP1, SP2, SP3 and SP4) were plotted for the four tested specimens as shown in **figure (7).**

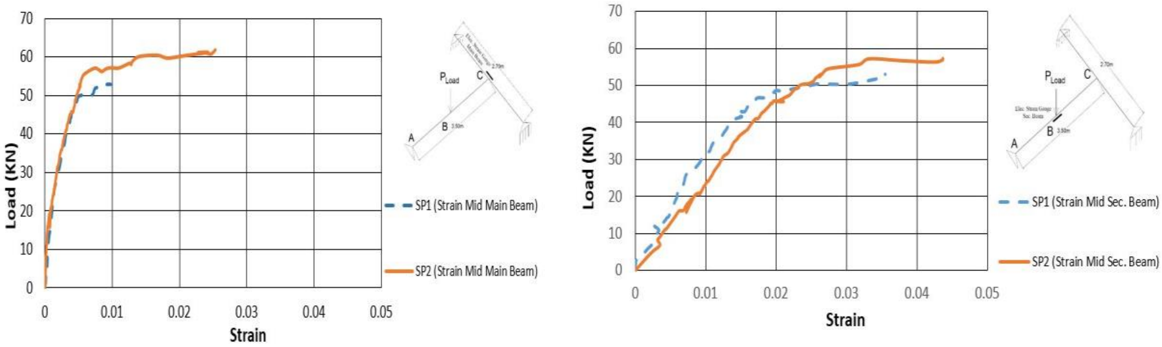


Figure (7) Experimental Results of Main Steel strain at
mid span of main and secondary beam for (G1)

From **figure (7)** the following remarks could be concluded:

For the tested specimens, tension strains of main reinforcement at mid span of main and secondary beam for T-shaped specimens are nearly linear at the early stages of loadings, up to the yielding load. However, once the yielding occurs, the strain increases rapidly. Figure (7) clears the effect of torsional reinforcement for main (spandrel) beam but at hinged intersection, that torsional reinforcement for SP2 improves behavior of T-shaped specimen, also its cleared that torsional reinforcement increased load failure for SP2 compared to SP1.

3.4 Reaction

3.4.1 Load-Reaction relationship for specimens

The experimental results of load load-reaction curves at free end of secondary beam of models (SP1 and SP2) were plotted for the two tested specimens as shown in **figure (8).**

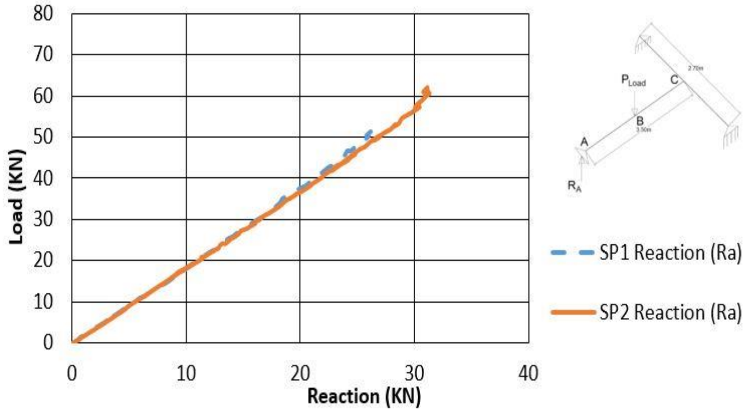


Figure (8) Experimental Results of load-reaction curves
at Roller Support of secondary beam for (G1)

From **figure (9)** the following remarks could be concluded:

For the tested specimens, load-Reaction curve is linear for two specimens, reaction at free end of secondary beam is approximately one-half failure load for all specimens, but it's cleared that torsional reinforcement for main beam increases failure load for SP2 compared to SP1 consequently increases in reaction at free end on secondary beam.

5 CONCLUSIONS

Based on the obtained experimental and numerical results, the following main conclusions can be drawn:

1. Torsional reinforcement as in specimens (SP2&SP4), increases main beam capacity, reaction at roller support and deflection at mid span of main beam.
2. Torsional reinforcement by means closed stirrups for main beam (spandrel beam) when intersection joint is a hinged one increased the load carrying capacity by 12.44 % more than the main beam which has no torsional reinforcement and improve the general deformational behavior of these T-shaped frames, this may attribute to that, this reinforcement increases the torsional rigidity and failure load.
3. Torsional reinforcement by means closed stirrups for main beam (spandrel beam) when intersection joint is a fixed one increased the load carrying capacity by 6.22 % more than the main beam which has no torsional reinforcement and improve the general deformational behavior of these T-shaped frames, this may attributed to that, this reinforcement increases the torsional rigidity and failure load.
4. Fixation joint at intersection by increasing negative tension stress to three times its value improves load- rotation curves and improves the general deformational behavior of these T-shaped frames, this may attributed to that, this longitudinal reinforcement increases the torsional rigidity and failure load.
5. Increasing longitudinal steel bars at intersection joint, and using closed stirrups for spandrel beam decrease the deflection, decrease torsional cracks at spandrel beam and improved failure load and deformation behavior.
6. Fixation joint improved the behavior of T-shaped frame, by redistribution of torsional moment to positive flexural moment near mid span of the floor beam leads to more economic design because the flexural capacity of a typically reinforced concrete section is significantly larger than its torsional capacity.

6 REFERENCES

[1]- Collins, M. P., and Lampert, P., "Redistribution of Moments at Cracking, The Key to Simpler Torsion Design", Analysis of Structural Systems for Torsion, SP-35, American Concrete Institute, March 1973.

[2]- Onsongo, W. M., "Longitudinally Restrained Beams in Torsion", M.Sc. thesis, Department of Civil Engineering, University of Toronto, Toronto, Ontario, Canada, 1972.

[3]- ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-02) and Commentary (318R-02)", American Concrete Institute, March, 2002.

[4]- CSA Standard, "Design of Concrete Structures (A23.3-94)," Canadian Standards Association, Ontario, Canada, 1994.

[5]- Khaldoun Rahal, " Compatibility Torsion in Spandrel Beams Using Modified Compression Field Theory", ACI Structural Journal, MAY 2006.

[6]- Ozerdinc, M. E., Lampert, P.; and Collins, M. P., "Torsion-Bending-Redistribution at Cracking-An Experimental Investigation", Civil Engineering Publication No. 72-73, University of Toronto, Toronto, Ontario, Canada, Dec. 1972.

[7]- Hsu, T. T. C., and Burton, K. T., "Design of Reinforced Concrete Spandrel Beams," Journal of the Structural Division, Jan.1974.

[8]- Hsu, T. T. C., and Hwang, C., "Torsional Limit Design of Spandrel Beams," ACI JOURNAL, Feb. 1977.

[9]-American Concrete Institute “Report on Torsion in Structural Concrete, AC1 445.1R-12”, Aprial 2013.
[10]- Abul Mansur, M., and Rangan, V., “Torsion in Spandrel Beams,” Journal of the Structural Division, July 1978.
[11]- ACI Committee 318, “Building Code Requirements for Reinforced Concrete (ACI 318-63),” American Concrete Institute, Farmington Hills, June 1963.
[12]- ACI Committee 318, “Building Code Requirements for Reinforced Concrete (ACI 318-71),” American Concrete Institute, Farmington Hills, 1971.
[13]- Mo, Y. L., and Hsu, T. T. C., “Redistribution of Moments in Spandrel Beams,” ACI Structural Journal, Jan-Feb 1991.
[14]- Vecchio, F. J., and Collins, M. P., “Predicting the Response of Reinforced Concrete Beams Subjected to Shear Using the Modified Compression Field Theory,” ACI Structural Journal, May-June 1988.
[15]-Abdul Razzaq, Adi.A. “Strength and behavior of reinforced concrete spandrel beam under the repeated loads” M.Sc. Thesis, College of Engineering , University of Basra 1998.
[16]- Rahal, K. N., and Collins, M. P., “Analysis of Sections Subjected to Combined Shear and Torsion-A Theoretical Model,” ACI Structural Journal, July-Aug. 1995.
[17]- Rahal, K. N., and Collins, M. P., “Combined Torsion and Bending in Reinforced Concrete Beams,” ACI Structural Journal, Mar.- Apr. 2003.
[18]- Rahal, K. N., and Collins, M. P., “Effect of Thickness of Concrete Cover on Shear and Torsion Interaction-An Experimental Investigation,” ACI Structural Journal, May-June 1995.
[19]- Khalaf, Yacob.Y, ”Strength and behavior of reinforced concrete spandrel beam under repeated loads”
M.Sc. Thesis, College of Engineering , University of Basrah 2002.
[20]- Jawad, N.A.M., “Strength and Behaviour of Reinforced Concrete Spandrel Beam”, Msc.Thesis, College of Engineering, University of Basrah,1988.
[21]-Thomas T. C. Hsu and Y. L. Mo, “ Unified Theory of Concrete Structures, 2010 John Wiley & Sons Ltd”.
[22]- Mashhour Ghoneim, Mahmoud El-Mihilmy, “ Design of reinforced concrete structures”, Vo.1, Second Edition, 2008.