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TORSIONAL BEHAVIOR OF REINFORCED CONCRETE EDGE BEAMS CARRYING PRECAST SLABS

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الملخص العربى:
يهدف هذا البحث دراسة مدي تأثير الإلتواء علي الكمرات الخرسانية الطرفية التي تحمل بلاطات خرسانية سابقة الصب وكيفية مقاومة هذا الإلتواء. تم دراسه عينة من الخرسانه المسلحة مكونة من كمرتين طرفيتين ذات قطاع مستطيل و بلاطة سابقة الصب بسمك 20 سم محمولة علي الكمرات و ذلك بطول اتصال 10 سم (نصف عرض الكمرة) بين البلاطة و الكمرات و تم صب طبقة خرسانة بسمك 5 سم فوق النظام الانشائي للبلاطة و الكمرات وتم التأثير بحمل خطي علي البلاطة حتي الأنهيار وكان المتغير الرئيسي في هذة العينة هو الاختلاف في نسب تسليح الكمرات التي ستقاوم عزوم اللي والقص حيث أنه لم يتم الأخذ في الاعتبار التسليح المقاوم لعزوم اللي في احدي الكمرتين و تم تسليح الكمرة الأخري بنسبة 50% من التسليح المقاوم لعزوم اللي و كل كمرة لها نفس الأبعاد و تم تعيين حمل الأنهيار للعينة والترخيم والحركه الأفقيه والأنفعال بالحديد الرئيسي وتم عمل تحليل بطريقة العناصر المحددة للتحقق من النتائج التى تم الحصول عليها معمليا. و بصفة عامة، كان هناك توافق كبير بين كل من النتائج المعملية و العددية.وتم عمل أستنتاجات ومقترحات من هذا البحث.

ABSTRACT

Torsion in RC beams is usually associated with bending moments and shearing forces, and the interaction among these forces is important. Thus, the behaviour of concrete elements in torsion is primarily governed by the tensile response of the material, particularly its tensile cracking characteristics. When torsion acts on an RC member, it forms two orthogonal diagonal loops in which one of them is in compression, which is generally resisted by concrete, and the other in tension, which is generally resisted by steel or other reinforcements. This research focused on the study of torsional behaviour of reinforced concrete edge beams carrying precast slabs specifically when the details of reinforcing steel in beams (stirrups and longitudinal steel bars resist torsion) are different. In this study, the torsional behaviour of reinforced concrete edge beams carrying precast slabs under failure line load was studied, where the details of steel reinforcement in beams are different to get the appropriate steel reinforcement ratio can be used for resisting torsional moment in beams (rectangular, L-shaped beams and ring beams). A numerical investigation utilizes the non-linear finite element modelling (FEM) was performed in ANSYS® to validate the experimental results. Overall, the numerical results agreed very well with the corresponding experimental results at all stages of loading.

KEYWORDS
Precast Concrete, Torsional, Rectangular beams, Ledge beams, Edge beams, Non-linear structural analysis and Finite element analysis.

1 INTRODUCTION

In the past decades, extensive research has been conducted to investigate the response of plain and reinforced concrete (RC) structures subjected to pure torsion. Torsion is considered a predominant action in structures such as curved girders, eccentrically loaded box beams, spandrel beams, and spiral stair-cases. In addition, Structural members subjected to torsion can be found in different shapes such as T-shape, inverted L–shape, double T-shapes and box sections, which makes the understanding of torsion in RC members, is a complex task. The torsional moments in beams are generally categorized into two types: primary and secondary torsion. Primary torsion, also known as equilibrium torsion, is basically a strength problem by which the members fail when torsional loads exceed torsional strength of the member. This can be mainly seen in statically determinate structures. On the other hand, secondary torsion, which is the result of continuity requirements in statically indeterminate structures, is the latter category which in some instances can cause colossal damage when continuity requirements are neglected.

Hence, this research was conducted to achieve the following objective:

1- Investigation of the torsional behavior of reinforced concrete edge beams (failure behavior) carrying precast slabs. Also this investigation can lead to increase the efficiency of reinforced concrete beams to gain resistance against pure torsional moments.
2- As the behavior of torsion in beams is dependent on a number of factors relevant to their geometry; amount and detailing of reinforcement, concrete strength and loading pattern, it is focused on steel reinforcement ratios of beams resisting torsion to be different in order to determine the appropriate ratio.

Study was implemented depending mainly on static analysis and design regulations of the Egyptian code for the design & construction of reinforced concrete buildings. In recent years the evolution of computer technology has advanced to the stage where the finite element method (through codes such as ‘ANSYS’) can realistically be used to model full-scale buildings and subject them to a variety of loads, including seismic. Modelling through a detailed finite element discretisation of the structure can provide a more realistic representation of the actual behaviour of RC buildings. Therefore in this research the theoretical models of beam - column joints of RC framed structures were implemented using ANSYS computer package ver.14.

2 EXPERIMENTAL PROGRAM

The experimental work of the present study consists of testing one specimen reinforced concrete.

2.1 Test Specimen

This research consists of one specimen (S1) the main variable of specimen is difference in steel reinforcement details designed to resist bending moments, shear stresses and torsional moments of beams were tested in the laboratory and labelled with B1 and B2. Each beam will be studied and analyzed under the effect of different steel reinforcement ratio. The beams have the same dimensions but differ in the steel reinforcement. The specimen has two beams 2000 mm long, 200 mm width and 270 mm depth and one slab with dimensions 1500 mm long, 1000 mm width and 200 mm depth and the layer above the slab/beam system with dimensions 1500 mm long, 1200 mm width and 50 mm depth. Specimen dimensions, amount of main steel reinforcement and concrete strength, as shown in **table (1). Fig. (1)** shows the geometry and reinforcement details of the tested specimen.

Table (1)*: Description of the Tested specimen*

Specimen NO.	Dimensions (mm)				Main Reinforcement							Stirrups In Beams	Concrete Strength f_{cu} (N/mm^2)	
	Beams		Slab DIM.	In Situ Concrete Layer	Beams			Slabs					Beams And Slab	In Situ Concrete Layer
	Beam NO.	DIM.			Main Steel	At mid depth	Secondary Steel	Bottom Mesh		Upper Mesh				
S1	B1	200*270*2000	1000*1500*200	1200*1500*200	4∅16	-----	2∅10	16 ∅ 16/ 1.5M	6 ∅ 12/ 1M	9 ∅ 10/ 1.5M	6 ∅ 10/ 1M	8Ø6/m'	40 N/mm^2	25 N/mm^2
	B2				4∅16	2∅10	3∅10					7Ø8/m'		

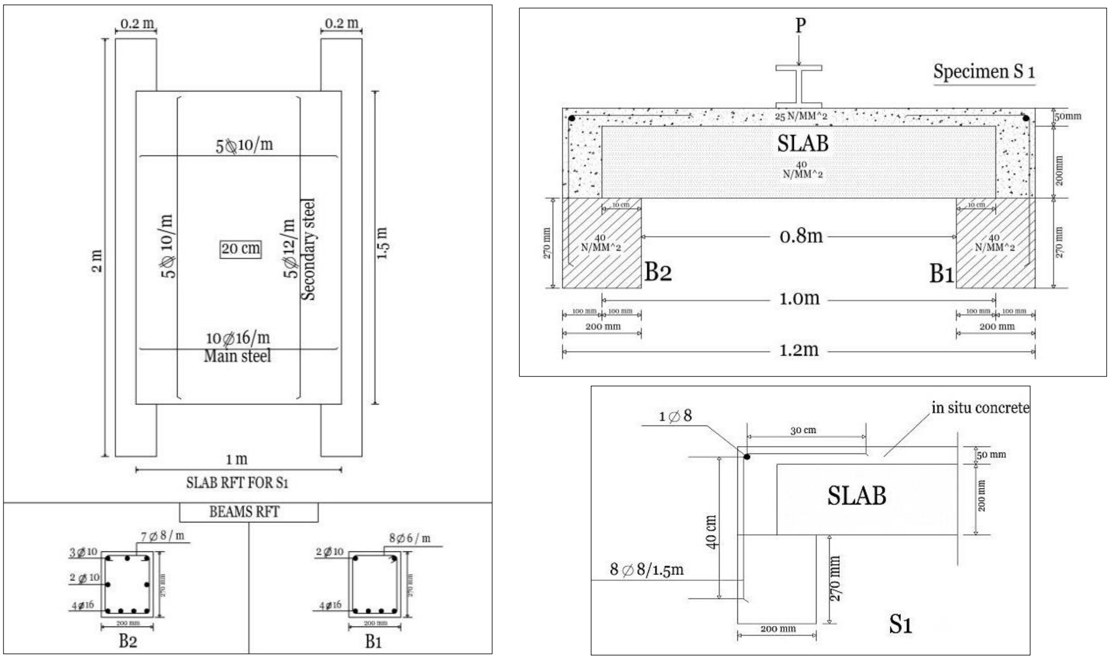


Fig. (1): *Steel Reinforcement Details of beams and slab of tested specimen*

2.2 Equipment and Instruments:

The specimen was tested in the RC laboratory of Ain Shams University directly by applying a line load at the top of the slab for S1 as shown in **Fig. (2)**.

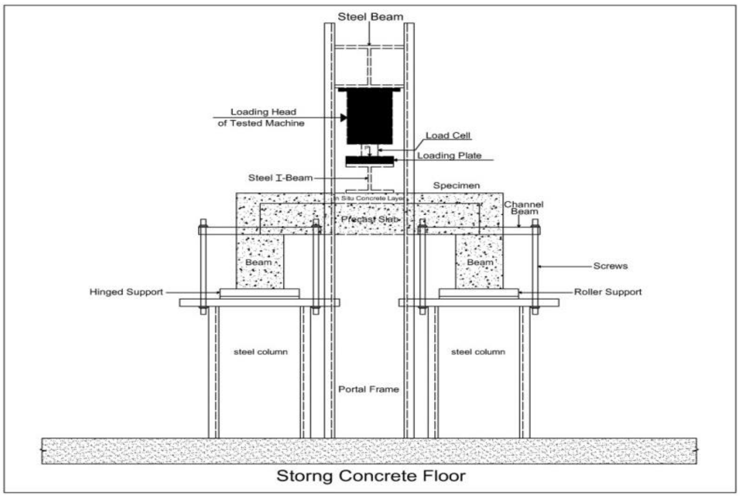


Fig. (2): *Testing Set-Up for specimen*

2.2.1 Measuring devices:

Two linear variable displacement transducers (LVDT) with 120 mm range were used to measure the beams (B1 and B2) deflection at the mid span of beam and three linear variable displacement transducers (LVDT) with 120 mm range were used to measure the slab deflection at three points distributed at equal distances every 37.5cm along the span of slab. The strains in steel bars were measured using electrical strain gauges with 120.4±0.4 ohm resistance. **Figure (3)** Show general arrangement for deflectometer and electrical strain gauges for specimen.

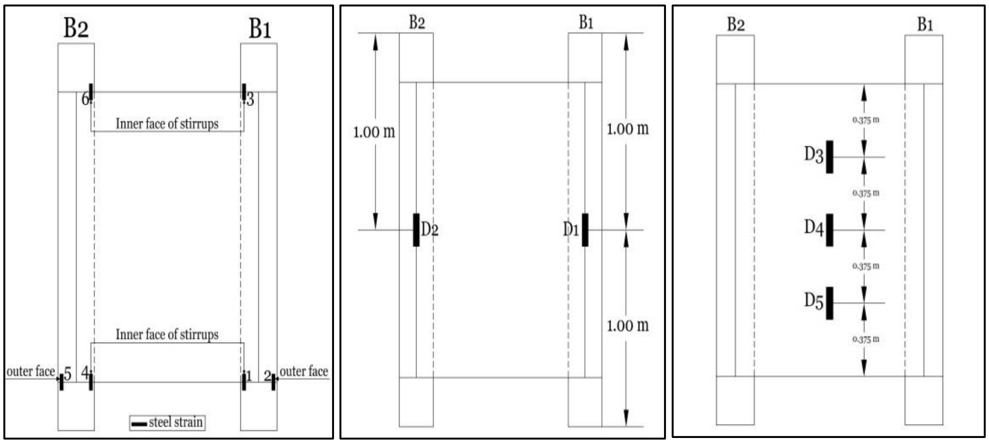


***Fig. (3):** General Arrangement for Deflectometer and Electrical Strain Gauges For Beams and slab*

2.3 Test Procedure:

The specimen was tested using an incremental static loading procedure. Firstly the applied load on the slab was around 10% of the failure load for the purpose of specimen installing, Secondary the applied line load on the slab started upon the failure. All the readings of beams and slab deflection, compression and 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 30 minutes for this specimen.

3 EXPERMENTAL RESULTS

3.1 Crack Patterns, Cracking Loads and Failure Loads

The first crack occurred in the mid-span of beam B1 outer face at load of about 40% of the failure load of the specimen. Further loading caused the crack to extend towards the inner face and shear zones at hinged & roller supports at load of about 75% of the failure load of the specimen. At load of about 80% of the failure load of the specimen, some small number of hair diagonal cracks appeared in the shear zone of the beam B2 at hinged & roller supports. Finally when the load reaches failure load (994 kN), extensive damage and explosion were observed and global collapse of the specimen S1 in the shear zones of the beam B1 occurred. Also in-situ concrete layer crushed and separated the slab at load of about 60% of failure load. **Table (2),** shows the cracking load at which the first crack appeared, the failure load and the maximum deflection of beams and slab at failure load. **Figure (4)** show the general crack patterns for the tested specimen.

__Table (2)__: Experimental Results of Cracking Load, Failure Load

Specimen NO.	Concrete Strengths f_{cu} (N/mm²)		The Load Of First Crack (KN)	Ultimate Load P_f (KN)	Maximum Deflection (mm)		BEAM That Failure First
	Beams And Slabs	In Situ Concrete Layer			BEAMS	SLAB	
S1	40	25	400.00 - B1	994.71	13.22 – B1 10.07 – B2	16.33	B1

__Figure (4):__ General Crack patterns of Specimen (S1)

From **table (2) and figure (4),** the following remarks could be concluded:

For the tested specimen (S1), In general, the specimen S1 failed due to excessive diagonal deep cracks in the beam B1 in shear zone near the supports and excessive crack & crushing in the slab due to shear at failure load of 994 kN. Regarding of failure loads, crack patterns and twisting of the beams (B1 and B2), the result analyses indicates to that the beam (B2) resist torsional moment and twisting than beam (B1) result of increasing the steel reinforcement percentage (stirrups and longitudinal steel bars) that resist torsional moment of the beams.

3.2 Deflection

3.2.1 Load-beams deflection relationship of specimen

The experimental results of load-beams (B1, B2) deflection curves at mid span of beams (D1, D2) were plotted for the tested specimen as shown in **figure (5).**

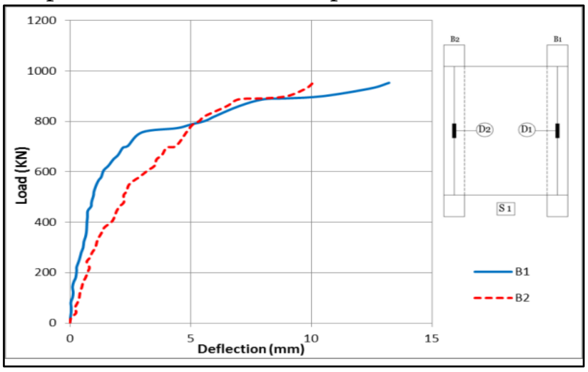


__Figure (5):__ Experimental Results of R – Deflection Curves at mid of beams

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

For the tested specimens, the maximum beam deflections (D1 & D2) at failure load of specimen S1. Figure and table demonstrates that deflection (D2) of beam (B2) is less than deflection (D1) of Beam (B1) with percentage 25% that the failure occurred in B1 first.

From these figure, it can be noted the effects of difference in steel reinforcement ratios on beams deflection that the beam B1 designed to has zero steel ratio against torsional moment and B2 having 50% steel ratio. Figure and table demonstrate that deflection of beam B2 decreases from B1 with percentage 25% due to the difference in steel ratios (0% and 50%).

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.

3.2.2 Load-slab deflection relationship of specimen

The experimental results of load-slab deflection curves measure at three points distributed at equal distances every 37.5cm along the span of slab (D3, D4 and D5) were plotted for the tested specimen as shown in **figure (6).**

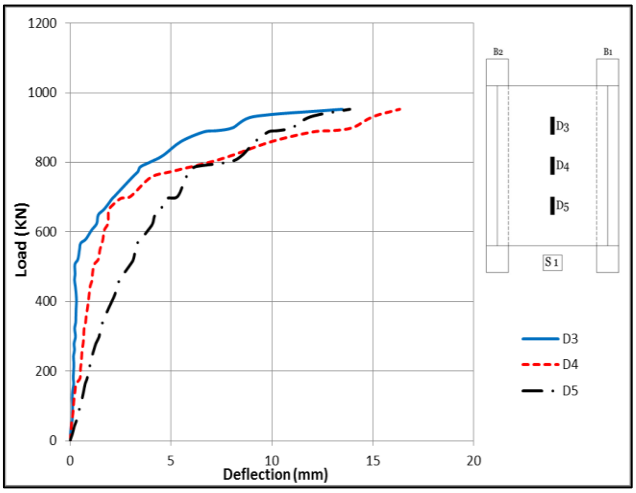


Figure (6): *Experimental Results of R – Deflection Curve of slab*

Regarding the deflections of slab (D3, D4 and D5), figure above demonstrates clearly the effects of steel reinforcement ratio increasing of model beams (B1 and B2) on slab deflections. As the concrete strength, size, stiffness are the same for model beams but differ in steel ratios; the main affecting factor on slab deflections is the increasing of model beam steel ratios against torsional moments.

3.3 Strains

3.3.1 Load-stirrups strain relationship for beams

The experimental results of load load-strain curves for the beam stirrups of the beams (B1 and B2) were plotted for the two tested beams as shown in **figure (7).**

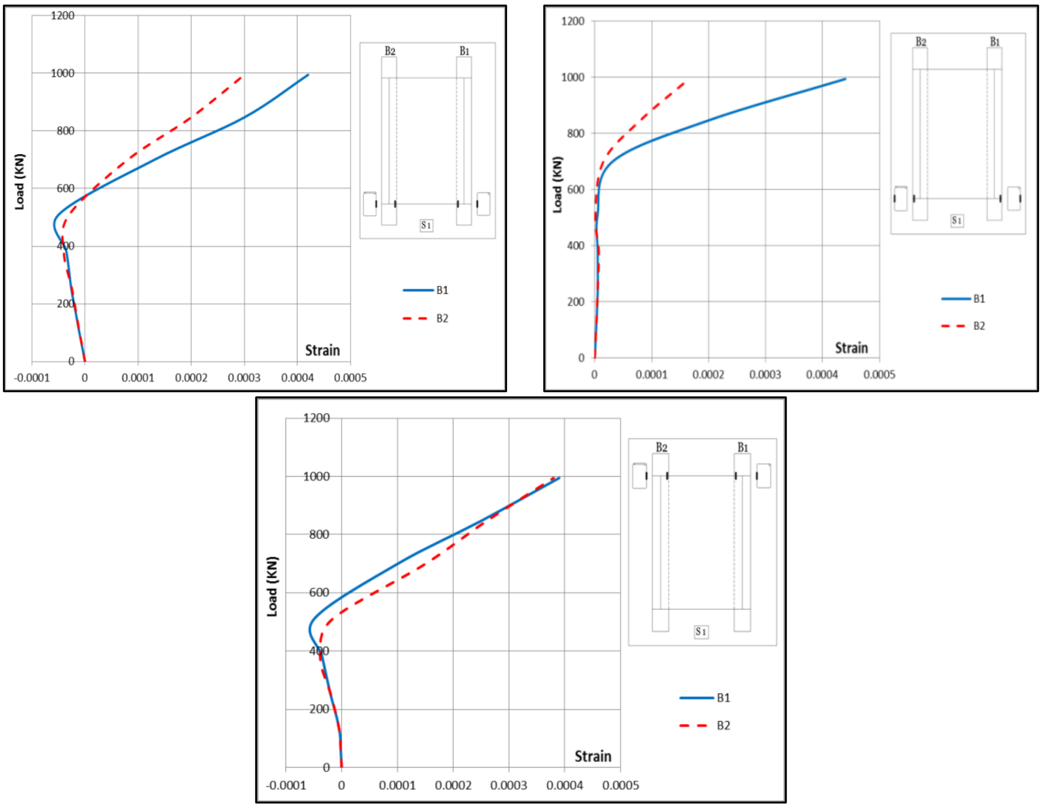


Figure (7): Experimental Results of R – Strain of Stirrup Curves

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

For the tested specimen, Strains NO. (1 & 3) in beam B1 and Strains NO. (4 & 6) in beam B2 are located on the stirrups that used to resist torsional moment at the inner face such this stirrups are located at the maximum shear zone in the beams (B1 & B2). Strain NO. (2) in beam B1 and Strain NO. (5) in beam B2 are located on the stirrups that used to resist torsional moment at the outer face such this stirrups are located at the maximum shear zone in the beams (B1 & B2). Also the figure (7) reveals that the strains of curves 1, 2, 3, 4, 5 & 6 (Stirrups) are in compression zone & tension zone and directly proportional with load increasing till failure as expected. All relations are commonly linear & nonlinear behaviour.

- Maximum strains of beam (B1, B2) stirrups at locations 1, 2, 3, 4, 5 and 6 as shown in figure (7) at inner & outer face of stirrups are tensile strains. The maximum strains of beam B1 stirrups (locations 1, 2 and 3 corresponding to beam B2 locations 4, 5 and 6) are more than maximum strains of beam B2 stirrups (locations 4, 5 and 6) with average percentage 31.2%. This means that when torsion effects of B1 were not be taken into account with respect to steel reinforcement (stirrups and longitudinal steel bars), the strains due to torsion effects increased with average 31.2% more than B2 that the effects of torsion with respect to steel reinforcement were be taken into account with percentage 50% of design requirements of steel reinforcement due to torsional moments.
- As shown in figure (7), the strains of stirrup inner faces have become in compression zone firstly and after that in tension zone. Meaning of that under vertical line load the stirrup inner faces are compressed and with increasing of line load parallel with torsional moment occurrence of beams, the strain of stirrups convert from compression to tension strains. Also figure (7) demonstrated clearly

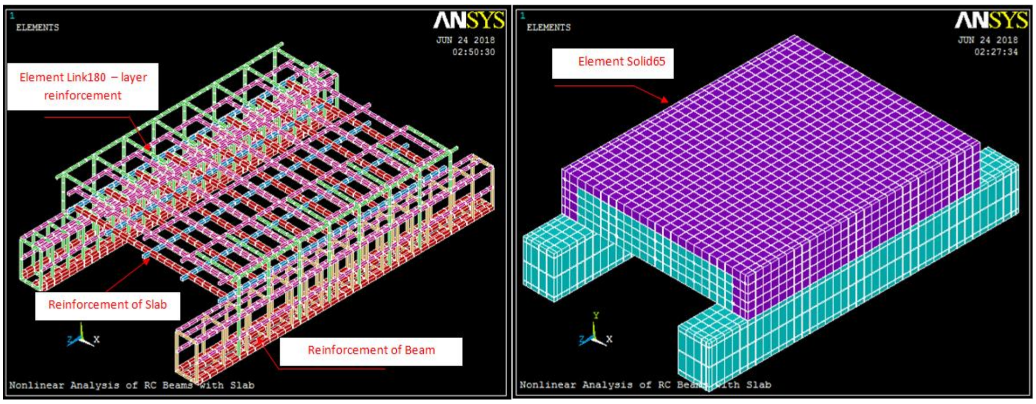
that the strains of stirrup outer faces of beams (B1, B2) are completely in tension zone due to the torsional moments.

4 FINITE ELEMENT MODEL

4.1 Methodology

The main aim of performing a finite element analysis of the model was to extend the investigations carried out experimentally to have better understanding of the behavior of the tested specimen.

The application of the appropriate boundary conditions for beam bases, which were assigned equal to zero for all degrees of freedom (creating hinged, roller supports for every beam and fixed ends to prevent twisting of beams and simultaneously the modelling of the fixation in experimental work). The main Three-dimensional finite element model of the RC precast slab / beam structure system model (S1) that were generated using ANSYS are shown in **Fig. (8)**. the differences between models are the details of reinforcing steel in beams (stirrups and longitudinal steel bars resist torsion). Concrete compressive strength (f_{cu}) and the type of loading are the same for the three models.



(a) **(b)**

Fig. (8): *F.E models*

(a) Figure 5-11: The main 3D finite element model of the S1 model (Precast slab / rectangular beams sections structure) – Difference between beams are details of reinforcing steel in beams.

(b) Steel reinforcement of the 3D finite element model of model (S1).

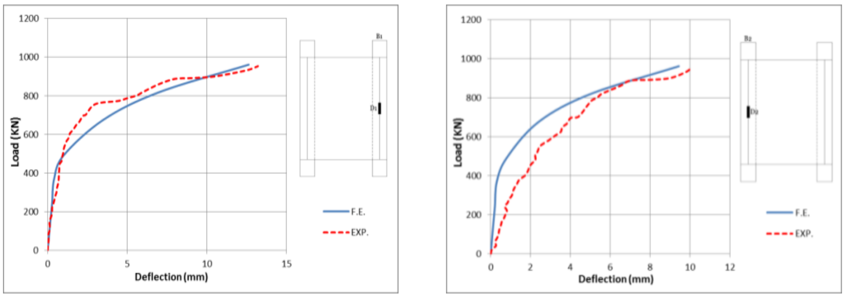
4.2 Results and Verification of FE Models

To verify the FE model, a comparison of the results from tests and those from the FE analyses was made; as shown in **Table (3).** It can be seen that the FE model captured the structural behavior in a satisfactory way. The maximum failure load resistances obtained in the FE analyses are equal to those obtained in the tests to within 5% difference.

__Table (3):__ Comparison for failure loads in Exp. and FE analysis

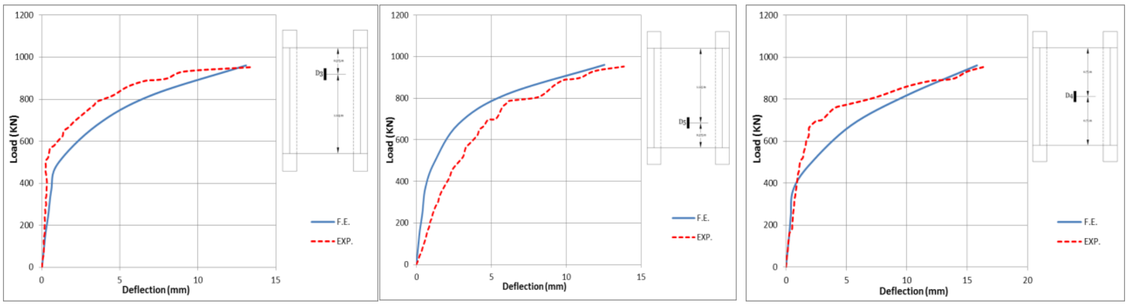
Model NO.	Concrete strengths f_{cu}(N/mm^2)		The Load of First crack (KN)			Ultimate Load (KN)		
	Beams and Slabs	In situ concrete layer	EXP.	F.E.A	$P_{EXP}/P_{F.E.A}$	EXP.	F.E.A	$P_{EXP}/P_{F.E.A}$
S1	40	25	400	370	1.08	994.71	961	1.035

Figures (9) and (10) show samples of comparisons between load- lateral deflection curves of the finite element analysis and test results obtained for specimen S1 (beams and slab) at the critical section. The model agreed well with the test results in terms of failure loads as well as the deformation and the strain values.



Beam (B1) *Beam (B2)*

Fig. (9): *Comparison between the Experimental and Analytical Load-beams deflection*



(D3) *(D4)* *(D5)*

Fig. (10): *Comparison between the Experimental and Analytical Load-slab deflection*

5 CONCLUSIONS

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

1. For rectangular beams tested under slab line loads, the failure load of specimen (S1) [steel ratio against torsional moment 0% of B1 & 50% of B2] is 994 kN.
2. With respect to the rectangular beams tested under slab line loads, the ratio of specimen failure load of S1 steel ratio 0% & 50% to S2 50% & 100% steel ratio is 0.9824. The difference in steel ratio between B1&B2 has a negligible effect on the failure load of S1 but has improved the torsional behavior more for B2.
3. The longitudinal steel reinforcement of beam at mid depth of B2 and stirrups were yielded which demonstrates clearly that failure occurs at shear zones of beams for all specimens due to occurrence of torsion for beams.
4. As the behavior of torsion in beams is dependent on a number of factors relevant to their geometry; amount and detailing of reinforcement, concrete strength and loading pattern, it is focused on steel reinforcement ratios of beams resisting

torsion to be different in order to determine the appropriate ratio. In general increasing of steel ratio of beams resisting the torsional moment effects will increase the resistance of beam sections, but may not need to full torsional steel reinforcement for all beams in the RC structure according to Egyptian code.

5. The simulation of specimens (precast slab/beams system) using F.E analysis in the ANSYS 14.0 program are quite well since mode of failure, failure loads and deflection of beams predicted were very close to those measured during experimental testing.
6. Results of the F.E. analysis showed good agreement with the experimental results with difference in rang of ±1.5%.

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