# EFFECT OF PRESTRESSING FORCE ON TORSION RESISTANCE OF CONCRETE BEAMS

**Prof .Dr .Husain M. Husain** — University of Tikrit

**Assist. Prof. Dr .Nazar K. Oukaili** — University of Baghdad

**Muyasser M. Jomaa'h** — University of Tikrit

## ABSTRACT

This study presents an experimental and theoretical investigation of torsion behavior of prestressed concrete rectangular beams without ordinary (or typical) reinforcement. Two concrete beams with concentric prestressing tendons (6-strands of 7 wires) and two plain concrete beams were tested in this investigation with f'c= 44MPa was used.

Experimental results showed that the ultimate torsional strengths increased by about 70% for the tested beams containing concentric prestressed strands over the plain concrete beams. Also the angle of twist decreased (68.8%).Crack patterns and the effect of compressive force due to prestressing tendons and high strength concrete can be denoted from the helical mode of single crack at midspan of the beams under testing and from the sudden failure mode. In the analytical work P3DNFEA (Program, three-dimensional nonlinear finite element analysis), by Al-Shaarbaf has been utilized. Three dimensional nonlinear quadratic 20 -node brick elements were used to model the concrete, while, the prestressing strands were modeled by embedded representation. Reinforcing bars (Prestressing strands) were assumed to be capable of transmitting axial forces only.

It was found that the general behavior of the finite element showed good agreement with observations and results from the experimental tests.

**KEY WORDS:** Concrete, FEA, Nonlinear analysis, Prestressed, Strands, Torsion.

## الخلاصة

تقدم هذه الدراسة بحثا عمليا ونظريا لتقصي سلوك اللي للعتبات الخرسانية المسلحة باستخدام حديدتسليح مسبق الاجهاد فقط (ظفائرتسليح عالية الصلادة) وذات مقطع مستطيل الشكل وبدون حديد تسليح إعتيادي. تم إعداد أربع عتبات خرسانية، اثنتان منها مسلحة باستخدام ستة ظفائر مركزية الموقع ومجهده مسبقا لاحداث تأثير قوى محورية مركزة على طول العتبة، والعتبتان الاخريان بدون أي نوع من انواع التسليح وتم فحص كل العتبات المعده في المختبر وباستخدام خرسانة عالية المقاومة تصل الى (٤٤ ميكاباسكال). اشارت النتائج المختبرية للفحص لفروقات زيادة ملحوظة في قيم مقاومة اللي تصل الى ٧٠% في العتبات المسلحة باستخدام الحديد المسبق الاجهاد عنه في العتبات الخالية من التسليح. إن نوع التشققات الناتجة تم تتبعها خلال مراحل الفحص المختبري وملاحظة نوع الفشل الحادث وسلوكية العتبات تحت

تأثير الاحمال المسلطة. تم استخدام برنامج الشعرباف في مقارنة النتائج المحصول عليها مختبريا من الناحية النظرية ووجد تقارب مقبول بين حالات الفحص ونتائج التحليل النظري حيث تم اعتماد نموذج طابوقي مكون من عشرين عقده لغرض تمثيل الخرسانة واعتمد العنصر المطمور لتمثيل عناصر حديد التسليح المستخدم، إضافة لادخال تأثير القوى المحورية في نفس العقد الممثلة لتلك العناصر الحديدية.

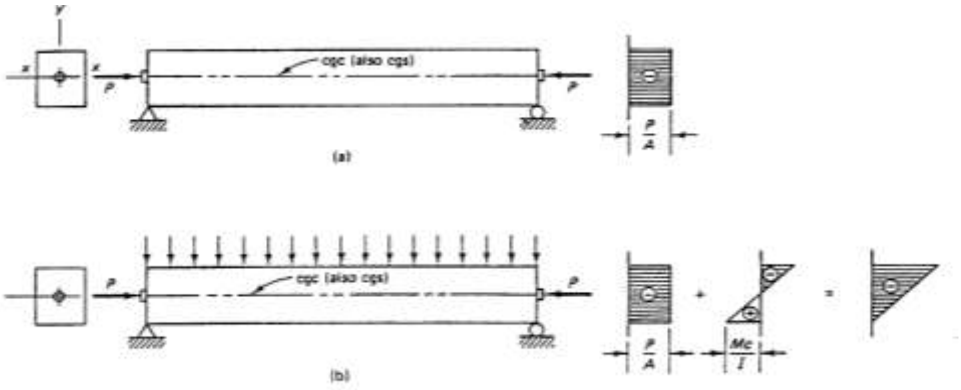
## INTRODUCTION

Prestressed concrete beams are used extensively in long span and other structures. The simplest form is the rectangular shape. Prestressed concrete members do not need large maintenance; a longer working life is possible due to better quality control of the concrete. Very large spans such as in segmental bridges or cable-stayed bridges can only be constructed through the use of prestressing, [Nawy, 2000].

The determination of the stress resultants (due to twisting moments or cross sectional distortion) and deformation in straight and curved, simple or continuous girders is complex and requires specified relationships between geometry, loads and deformations.

Concrete is strong in compression, but weak in tension: its tensile strength varies from 8 to 14 percent of its compressive strength [Lin and Burns 1982]. Due to such a low tensile capacity, flexural and torsional cracks develop at early stages of loading. In order to reduce or prevent such cracks from developing, a concentric or eccentric compressive force is imposed in the longitudinal direction of the structural element. This force prevents the cracks from developing by eliminating or considerably reducing the tensile stresses at the critical midspan and support sections at service load, thereby raising the bending, shear and torsional capacities of the sections. The sections are then able to behave elastically, and almost the full capacity of the concrete in compression can be efficiently utilized across the entire depth of the concrete sections when all loads act on the structure. Such an imposed longitudinal force is called a prestressing force; it is a compressive force that prestresses the sections along the span of the structural element prior to the application of the transverse gravity dead and live loads. Fig. (1).

The prestressing force (P) that satisfies the particular conditions of geometry and loading of a given element is determined from the principles of mechanics and from stress-strain relationship of concrete.




**(a) Concentric tendon, prestress only. (b) Concentric tendon, self-weight added**

**Fig. (1): Concrete fiber stress distribution in a rectangular beam with straight tendon [Lin and Burns 1982]**

A prestressed concrete beam shows considerably higher torsional stiffness and higher ultimate torque when compared with a plain concrete beam. This increase in torsional strength by the prestressing force may attributed to the higher inter-friction or interlocking force between the slices of the beam (Coulomb friction theory).The present study will show the extent of this effect.

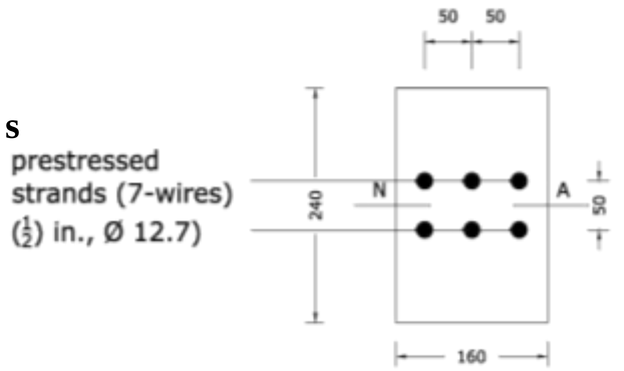
## EXPERIMENTAL STUDY

Four beams were tested in this investigation (2 groups): Group one included two samples of concrete beams with six strands only without typical ordinary reinforcement. These two samples were tested under pure torsion only. The strands were distributed on two layers at middle section (two layers) of (3 m) length. Group two include two samples of concrete beams without any type of reinforcement. Both of them were plain concrete of (2m) length and they were tested under pure torsion. Rotations due to applied loads were measured. The strains at many positions on the concrete faces (sides and upper surface) of the beams were recorded. The influence of prestressing force on the increase of ultimate torsion values was investigated. The concrete types (geometry and properties) were kept unchanged for both groups.

## TEST SPECIMENS

The nominal dimensions of the tested beams are shown in Fig. (2). A design equation adopted by ACI-318-0٥ Building Code was used to estimate the main factors of concrete strength and the torsional capacities.

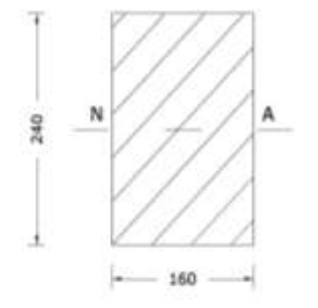
The main reinforcement consisted of (6-strands, 7-wires, $\phi$ 12.7 mm, 1/2 in.), passing grade 250ksi.




**(a)Six strands in cross-section**

**(b)Isometric view**

**Fig. (2): Details of test beams (Cross sections and isometric view of the samples, dimensions in mm)**




**(c)Cross-section of plain concrete beam**

**Fig. (2): continued**

## THE BASIC MATERIALS

Prestressed concrete utilizes high quality materials, namely high strength steel and concrete. All the materials were tested under standard specifications. In manufacturing the control and the test samples ,the following materials were used: ordinary Portland cement(Type I);crushed gravel with maximum size of (14mm);natural sand from Al-Ukhaider region with maximum size of (5mm) and fineness modulus of (2.84).The mix proportions for HSC are presented in Table(1).

Prestressing (7-wires) strand has the following components, $f_{py}$ = 1570MPa, $f_{pu}$ = 1770MPa, $A_{ps}$=93mm², Ø=12.7mm, 1/2 in. and E=195000MPa.

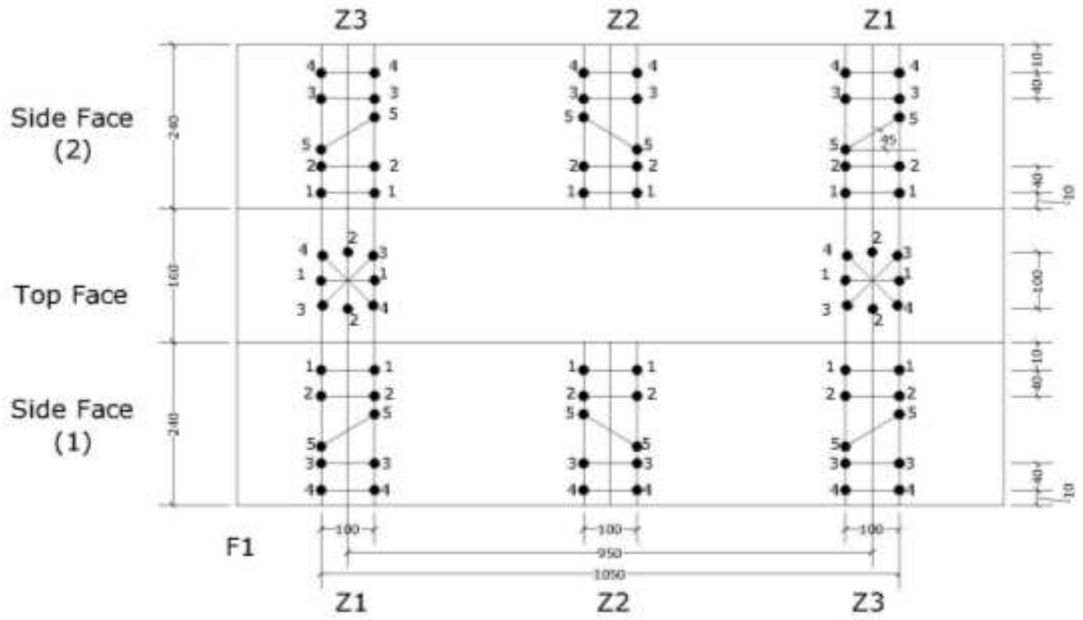
## Table (1) Concrete mix proportions

| Components | Quantities |
|---|---|
| Cement type I | 500 kg/m$^3$ |
| Sand (5 mm) | 600 kg/m$^3$ |
| Coarse aggregate (14 mm) | 1150 kg/m$^3$ |
| Water | 190 L/m$^3$ |
| Superplasticizer | 0 |
| Water / cement ratio (w/c) | 0.38 |
| Strength (cylinder 150*300 mm) | $(f'_c)$ = 35 MPa at 7 days<br>$(f'_c)$ = 42 MPa at 28 days<br>$(f'_c)$ = 50 MPa at 60 days |
| Density (γ) | 2440 kg/m$^3$ |

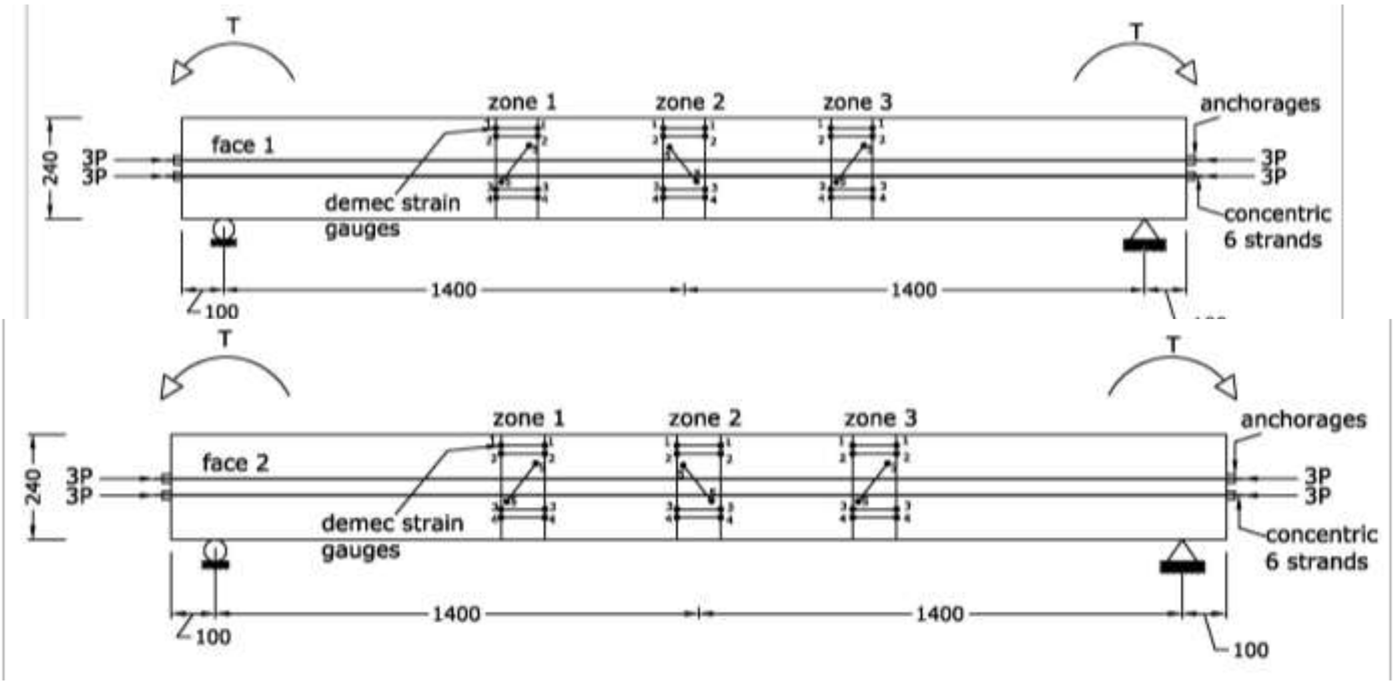
## TEST MEASUREMENTS AND INSTRUMENTATION

### INCREMENT OF STRAIN MEASUREMENTS (CONCRETE COMPRESSIVE AND TENSILE STRAIN)

The middle zone (1500 mm) of the total length of the specimens was determined as a measuring zone. The longitudinal concrete compressive strain and tensile strain at the extreme top and bottom fibers were measured above and below the neutral axis and at an inclined direction with ($45^o$), using demec strain gages. Demec gage points were placed at a spacing of 100 mm along the length of the measuring zone for all beam specimens, Fig. (3). The demec points can be seen at top face with shape of 4 points as a star, with respect to longitudinal axis or direction of the beam parallel to this axis, and in vertical and inclined directions which represent the expected strain directions under the applied torsional loading conditions, Fig. (3).




The prestressed concrete beams were with full prestressing, testing was under pure torsion, the concrete strain was investigated for compression and tension fibers, Fig. (4).




**B. demec strain gage nodes for ( side face 2)**

**Fig. (4): Concentric 6-strand beam under pure torsion with demec strain gages**

The strain diagrams for the concentrically prestressed concrete beams, represent the strain variation over the fibers and the behavior of concrete under pure torsion case (full prestressing), these are shown in Figs. (5) to (12).

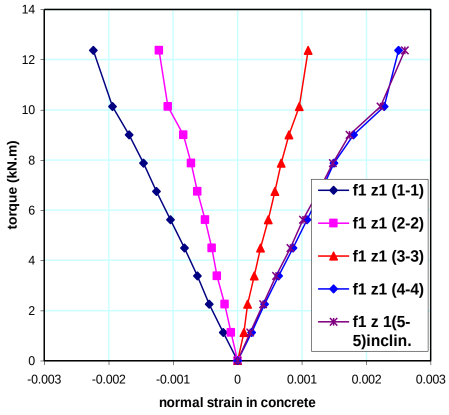



Fig.( 5 ):Torque-strain diagram in concrete (face1/zone1)

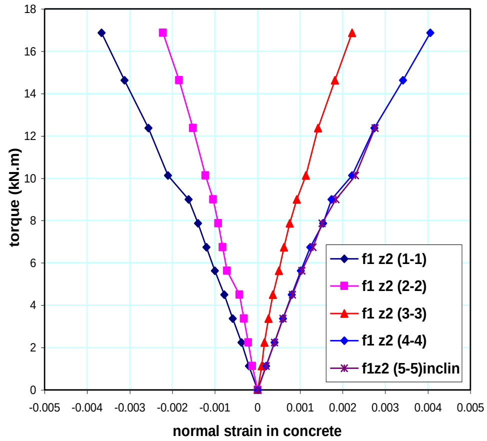



Fig.( 6 ):Torque-strain diagram in concrete (face1/zone2)

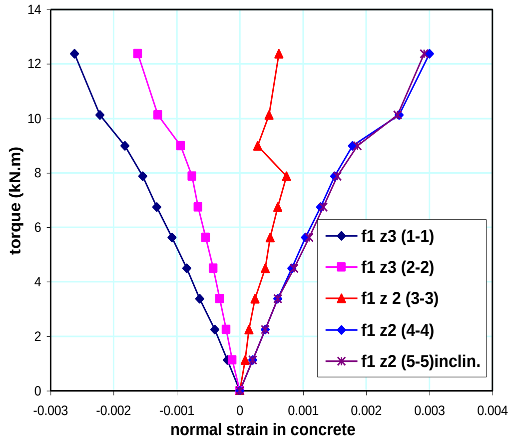



Fig.( 7 ):Torque-strain diagram in concrete (face1/zone 3)

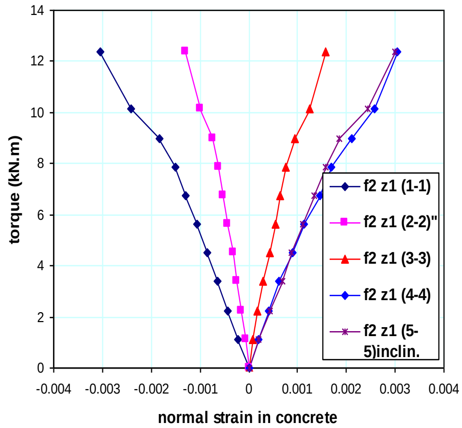



Fig.( 8 ):Torque-strain diagram in concrete (face2/zone1)

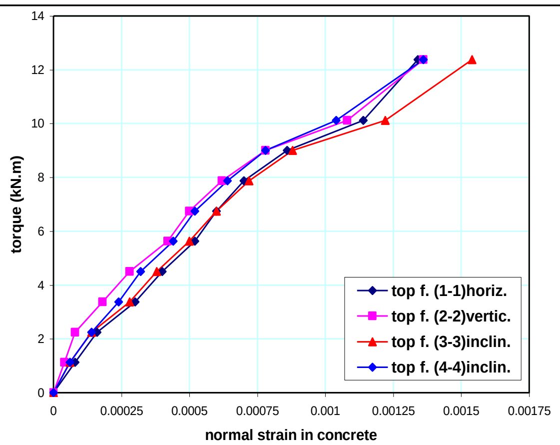



Fig.(12 ):Torque-strain diagram in concrete (top face,node 2)

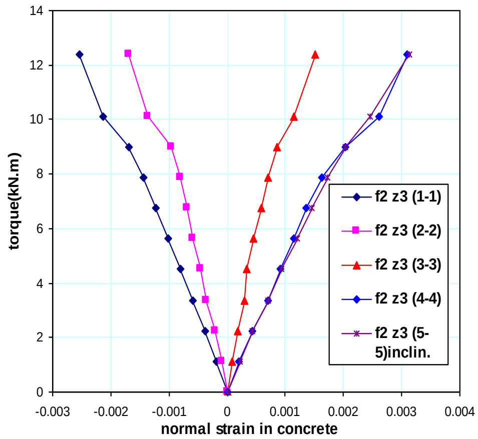



Fig.(10 ):Torque-strain diagram in concrete (face 2/zone 3)

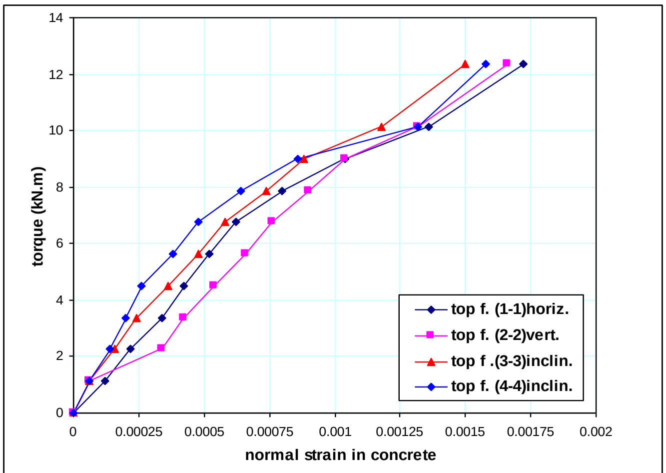



Fig.(11 ):Torque-strain diagram in concrete (top face,node 1 )

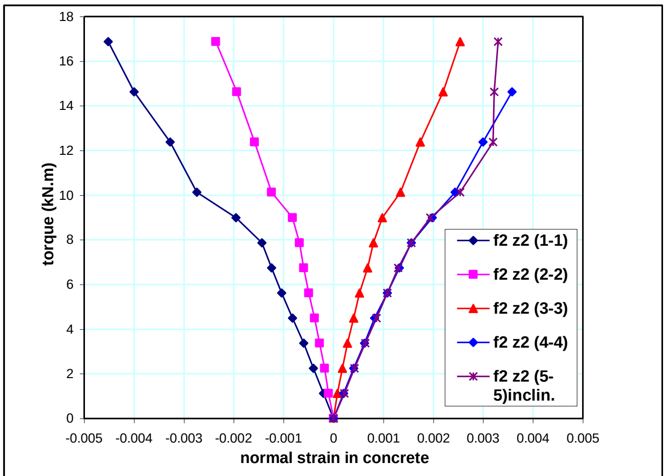



Fig.( 9 ):Torque-strain diagram in concrete (face2/zone2)

## ANGLE OF TWIST MEASUREMENTS

For the important application of prestressed concrete beams under the proposed type of this loading condition, pure torsion, the investigation of twisting angle is essential as a relationship with torque value, and also for estimating the torsional capacity of the prestressed concrete beams. A simple mechanical system was arranged with two dial gages in order to record the upward and downward deflection due to the effect of load (torque) on rotating the beam sample cross-section as shown in Fig. (13), within the increasing applied load.

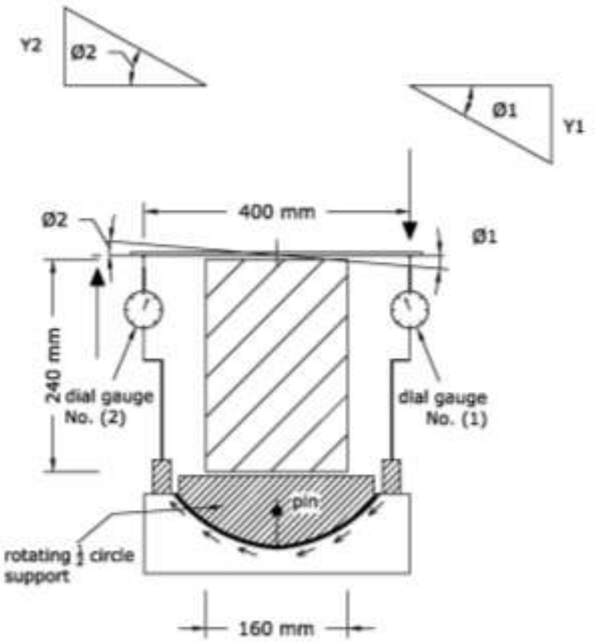



Fig. (13): Angle of twist instrumentation

## TEST PROCEDURE OF BEAM SPECIMENS

All beam specimens were tested as simply supported over an effective span of (2800mm) with symmetrical boundary conditions as shown in Fig. 14. Test started with the application of 2kN load to set and check the dial gages, then unloading to zero. At zero loading, initial readings of dial gages and mechanical strain gages (demecs) were obtained. The load was applied in (10 to 25) stages depending on the type of sample and loading conditions. At each loading stage, all the dial gages and strain gage (demec points) readings were taken. The interval between two consecutive stages was roughly 10 minutes. The overall testing time took an average 2 – 2.5 hours, depending on the deformation capacity of the beam tested. The load was continued until failure (defined as the highest capacity beyond which loading dropped) takes place, Fig. 14.

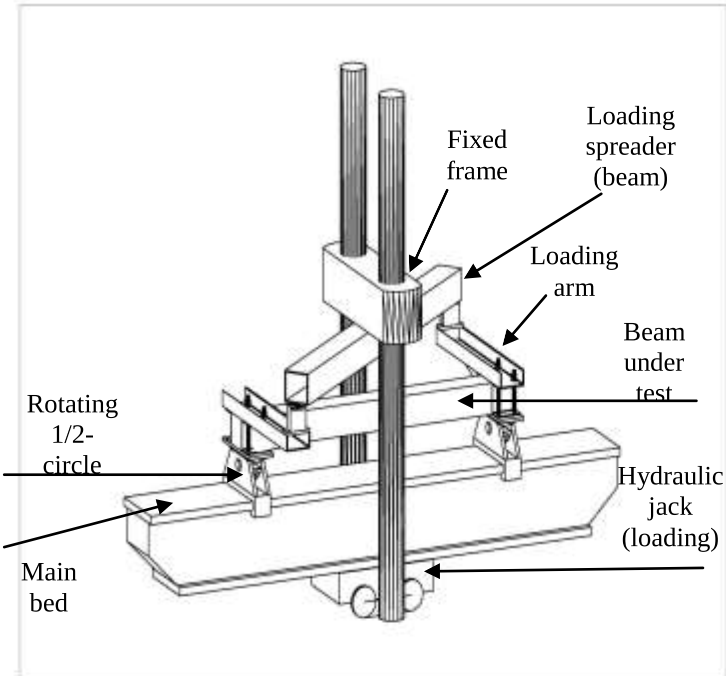


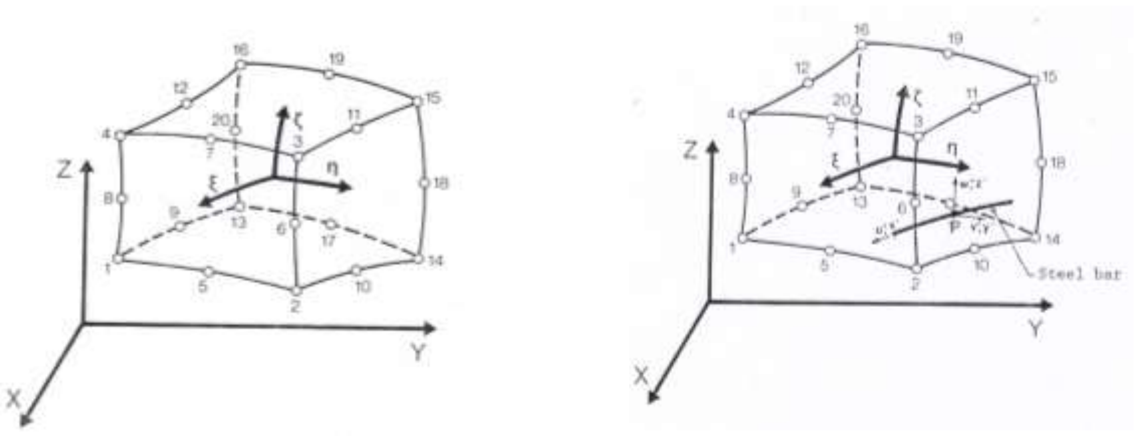

**Fig. (14): Concentric prestressed concrete beam sample under testing**

### THEORETICAL STUDY

In order to study the behavior of the prestressed concrete rectangular beams under the effect of torsion and to compare the results with the all tested beams, the nonlinear finite element program P3DNFEA [1] was used for this purpose.

### FINITE ELEMENT IDEALIZATION

In the present study, the chosen segments were modeled by using the quadratic 20-node brick elements as shown in Fig (15), for all length of the specimen (3m), in order to consider the effect of initial prestressing forces along the actual length. Longitudinal reinforcement was simulated as embedded one-dimensional elements in the brick elements. Since this study is devoted for the analysis of prestressed concrete beams, so more efficient prestressed models capable of being incorporated in a finite element solution were used.




**(a) 20-Node isoparametric brick element [1]**

**(b): representation of reinforcement (Embedded representation)**

**Fig. (15): Concrete idealization and reinforcing bar representation**

In this approach, the equivalent load method is used to compute the force applied by the tendon upon the structure where the prestressing tendon takes the form of a particular loading case and as such it may be taken into consideration in the form of appropriate local loads at the level of each element. Practically, this means that the effect of prestressing manifests itself in the evaluation of the vectors of primary nodal forces only.

The method is adopted here with the consideration that the tendon has straight profile along the beam and is fully bonded (prestressing by pretensioning) (no inclined or parabolic profile and without losses in tendons) and so the prestressing reinforcement was represented as embedded one-dimensional elements, with local coordinates. The straight tendon being in one level along the beam specimen.

## MODELING OF BEAMS

The actual dimensions of the tested beams with special reinforcement and loading conditions are shown in the figures below. Each two beams of group one (G1), had length (3m) and (160x240) mm cross-section, with concentric prestressing reinforcement only, and with no ordinary reinforcement, while the two beams of group two (G2), had length (2m) and

(160x240)mm cross-section, also without any type of reinforcement (plain concrete specimens). Both types of beams were tested under pure torsion to investigate the torsional capacity and the response by the angle of twist parameter and also the magnitude of the applied torque over these samples with effect of prestressing reinforcement, see Table (2).

**Table (2) Classification of concentric prestressing beams of plain concrete group with its properties under pure torsion.**

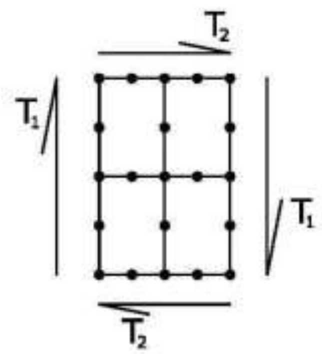
## MESHING AND LOADING CONDITIONS

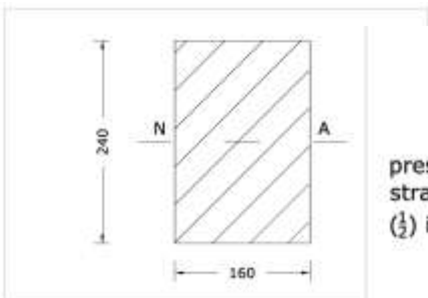
The behavior of the beams under torque was investigated using the angle of twist and the ultimate failure torque.

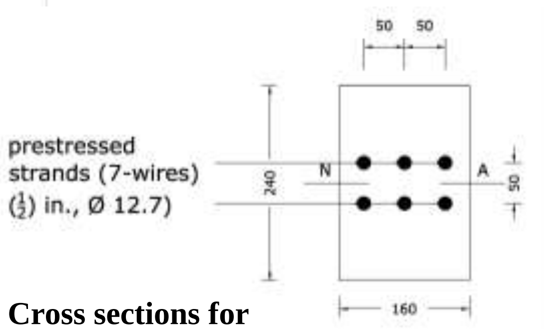
| Group No. | Beam No. | $f'_c$ (MPa) | Prestressing reinforcement No. of stands | | | Ordin. Reinf. | $f_{py}$ (MPa) | X-section | |
|---|---|---|---|---|---|---|---|---|---|
| | | | No. | A(mm$^2$) | dia. | | | b(mm) width | H (mm) depth |
| prestressed concrete beams (6 strands) | B1 | 42 | 6 | 558 | 12.7 | None | 1570 | 160 | 240 |
| | B2 | 43 | 6 | 558 | 12.7 | None | 1570 | 160 | 240 |
| plain concrete beams | B3 | 44 | | None | | None | None | 160 | 240 |
| | B4 | 43 | | None | | None | None | 160 | 240 |

The geometry and the finite element mesh and with the applied loading are shown in Fig. (16). The whole beam is modeled with 56 brick elements and a total number of 441 nodal points, as shown below.

Angle of twist will decrease due to initial prestressing force (as external axial load) if existing.

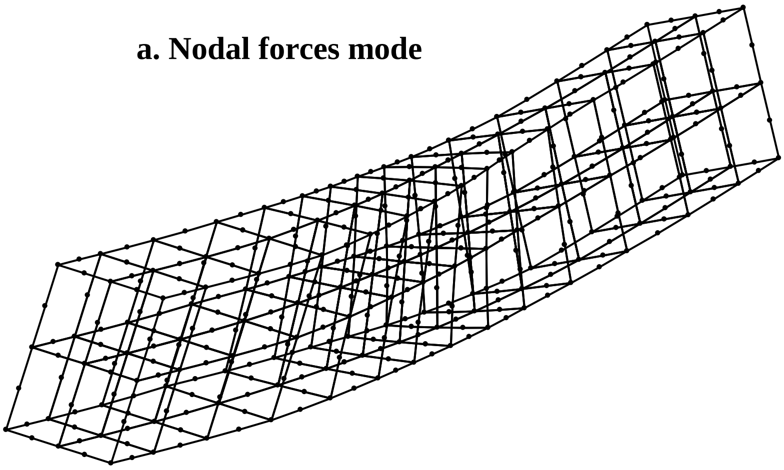


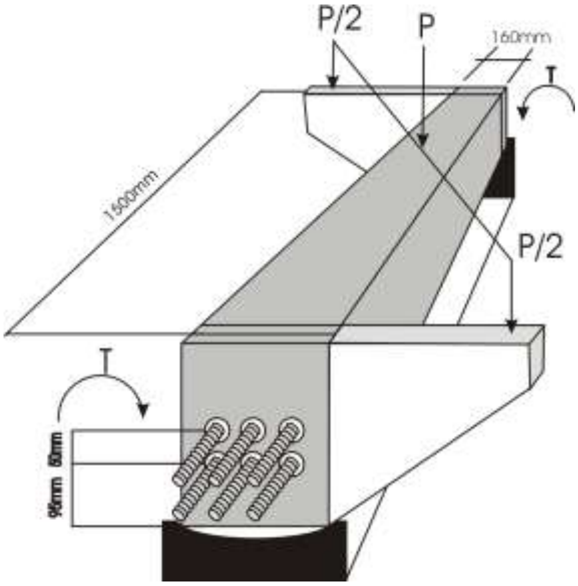




**b. Cross sections for prestressed and plain concrete beams**

**a. Nodal forces mode**






**c. Finite element mesh**

**d. Pure torsion case (concentric prestressing and plain concrete)**

**Fig. (16): Deflection of concrete specimen during test**

## RESULTS AND DISCUSSION

In Fig. (17), the torque-angle of twist relations of the concentric prestressed concrete beam with 6 strands is shown. While in Fig

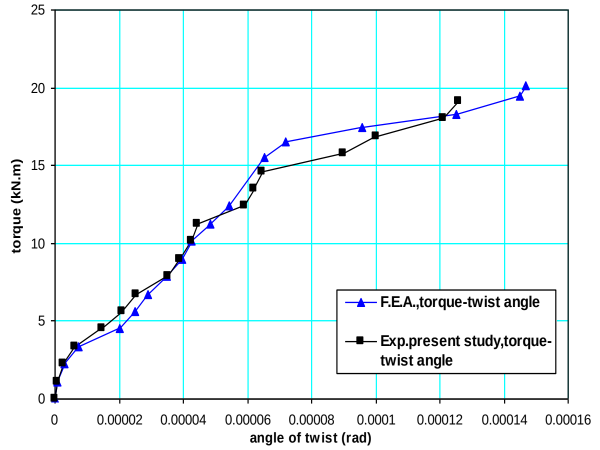



Fig.(17 ):Experimental and analytical torque -angle of twist diagram (concentric 6-strands prestressed beam under pure torsion )

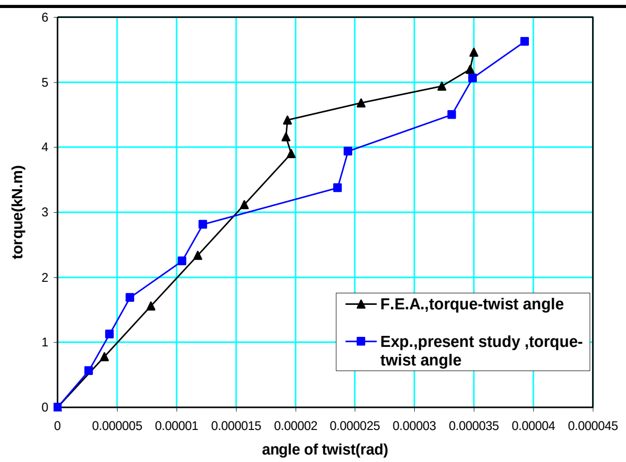



Fig.(18):Experimental and analytical torque-angle of twist diagram (plain concrete beam under pure torsion)

(18), the torque-angle of twist relation of the plain concrete beams is shown. Good agreement is obtained with experimental results. The values of the angle of twist decrease due to existence of initial prestressing force (as external axial load).

## GENERAL BEHAVIOR

All beams that were tested under pure torsion loading failed in torsion. At early loading stages, torsional cracks (spiral or helical cracks) were observed first in the middle zone of the beam (pure torsion region). As the load was increased, more torsional cracks developed in the pure torsion span. A main single crack with helical mode was generated at the midspan and gradually extending from side faces and from top and bottom of the sample. Clear cracks at the compressive region of the beam (top face) where the compressive stresses exist was found to increase due as the torsion load increases.This mode of failure associated with a diagonal tension cracks inclined at 45°, as shown in Fig. 19. Sudden failure (sudden seperation) occurred. The cracking patterns are similar for the samples of concentric prestressed members and the samples of plain concrete, with inclined angle approaching 45°. However the main difference is the drop of the failure load (torsional resistance) between prestressed beams and the beams of plain concrete, where presence of prestressing strands in the section reduces the angle of twist of concrete sample and thus increased the ultimate torsional resistance.


**Fig.(19):Failure of plain concrete beam under pure torsion loading**

## FAILURE MODE

The failure modes for the tested beams were the formation of diagonal tension crack (due to torsion load), as shown in Fig. 20. In table (3) the differences between experimental and theoritical results are presented.

**(a)Single diagonal crack mode failure for plain concrete sample**


**(b)Single helical crack for prestressed concrete beam with**

**Fig.(20): Modes of failure for plain and Prestressed concrete beams under pure torsion loads**

**Table (7.8): comparison of experimental and analytical results for all samples**

| Group No. | Beam No. | Type of load | Tult. Exp. (kN.m) | Tult. (max) F.E.A. (kN.m) | ult. Twist angle (θ) rad. Exp. | ult. Twist angle (θ) rad. F.E.A | % of diff. Tult. (kN.m) | % of diff. in (θ) rad. |
|---|---|---|---|---|---|---|---|---|
| **Group 1 (6-strands)** | B1 | (T)only | **19.125*** | 20.125 | $1.26x10^{-4}$ | $1.467x10^{-4}$ | 3 | 14 |
| | B2 | (T)only | **19.125** | 20.125 | $1.26x10^{-4}$ | $1.467x10^{-4}$ | 3 | 14 |
| **Group 2 (plain concrete)** | B3 | (T)only | **5.625*** | 5.46 | $3.926x10^{-5}$ | $3.207x10^{-5}$ | 1 | 18 |
| | B4 | (T)only | **5.625** | 5.46 | $3.926x10^{-5}$ | $3.207x10^{-5}$ | 1 | 18 |

***The main difference in values of ultimate torque that would be applied over the beams for plain and concentric prestress reaches to 73%.**

## CONCLUSIONS

Based on the results obtained from the experimental work and the finite element analysis for concentric prestressed and plain concrete beams, the following conclusions are presented:

1. Presence of the prestressed strands delays concrete failure and leads to higher failure load.

2. The ultimate torsional resistance is increased by 73% for the tested beams with prestressed strands relative to plain concrete beams.

3. The controlling crack propagation, the rate of cracks widening and the load carrying capacity are higher for the prestressed concrete beams relative to plain concrete beams.

4. The nonlinear finite element method utilized in this study has shown to be capable of reproducing the experimental response of the prestressed concrete beams. The isoparametric brick elements with embedded steel bars proved to be suitable for predicting the state of ultimate load, deflections and stress with good accuracy. The differences with experimental values (in deflection or ultimate load) were in the range (1-18%).

5. The effect of providing axial compressive force by prestressing was significant to get higher torsional resistance than in plain concrete beams. This phenomenon appeared pronounced in concentric prestressed concrete beams, where the ultimate torque increased considerably (more than 3 times) due to the applied compressive stresses on the sections.

## NOTATIONS

| | |
|---|---|
| $T_u$ | 1. Ultimate torsional moment |
| $f_c'$ | Compressive strength of concrete |
| $T_{uo}$ | Ultimate torsional capacity of beam subjected to pure torsion |
| $A_{ps}$ | Area of prestressing steel |
| $A_s$ | Area of reinforcing steel |
| $E_c$ | Modulus of elasticity of concrete |
| $E_{ps}$ | Modulus of elasticity of prestressing steel |
| $f_{py}$ | Yield strength of prestressing bar |
| x,y,z | Global coordinate system |
| $x', y', z'$ | Local coordinate system |
| $\varepsilon$ | Strain |
| $\sigma$ | Stress |

| | |
|---|---|
| **τ** | **Shear stress** |
| **ξ,η,ζ** | **Curvilinear coordinate system** |

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