*International Journal of Engineering & Technology*, 7 (4.20) (2018) 572-577

International Journal of Engineering & Technology

*Website: www.sciencepubco.com/index.php/IJET*

***Research paper***

# Flexural Behavior of Steel Beam Strengthening by Prestressing Strands

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**Abstract**

Seven simply supported steel beams were tested to explain the effect of strengthening by external prestressing strands. All of the beams have the same steel section, clear span length and the strengthening samples which implemented by two external prestressing strands. The tested beams are divided into two categories according to existing of external prestressing strands, the first category consists of one steel beam as a reference, while, the second group deals with steel beams strengthening by external prestressing strands and consists of six steel beams divided according to the eccentricity location of prestressing strand with jacking stress (815 MPa). From experimental results, it was found that the moment curvature curves behavior for the tested beams are stiffer and with less ductility than the reference beams and the ultimate moment capacity is increased with increasing the eccentricity location. While, the maximum radius of curvature at bottom flange decreases with increasing the eccentricity location as compare with the reference beam.

***Keywords***: *flexural behavior, strengthening of steel beams, prestressing strand, eccentricity location, external prestressing.*

## 1. Introduction

Steel is the most important construction material at the present time due to the high strength to weight ratio, uniform and homogeneous properties, high ductility, ability to be easily recycled, high elastic modules, high amount of energy absorption in seismic action, easier, quicker to fabricate and erect. Dimension of beams and column in steel frame can be reduced because of the low ultimate load to self-weight ratio. As a result, self-weight ratio between reinforced concrete and steel building can be reduced down to 1/10[1]. Producing permanent stress in the structural member to improve resistance against service loads is called as prestress or prestressing. Prestressing is a purposeful phenomenon aims to generate internal stress in structural member to counter balance stressed caused by external loads so as to enhance performance and durability of the structural members [2, 3].

## 2. External prestressing.

External prestressing refers to a posttensioning method in which tendons are placed on the outside of a structural member and prestressing forces are transferred to the structural member through anchorages and deviators. It is a wonderful method in strengthening and rehabilitation of old structural members, generally it is used for developing buildings and bridges for fatigue state and over loading design expected[4].
The concept of external prestressing of steel beams is achieved by means of high strength strand anchored at the two ends of steel beams. The strand profile can be fixed on the internal span length by a specific number of saddles which it prevents slipping occurs in the strand and help to give the design profile shape of the external prestressing strand (draped, or parabolic) depending on the applied load and bending moment diagrams introduced [5] as shown in Fig. (1).The strand them was tensioned simultaneously from one ends using the same jacking force used in tensioning the prestressing strand. Special care should be taken to balance the prestressing force in the strands to avoid biaxial bending and distortion of the specimens [6]

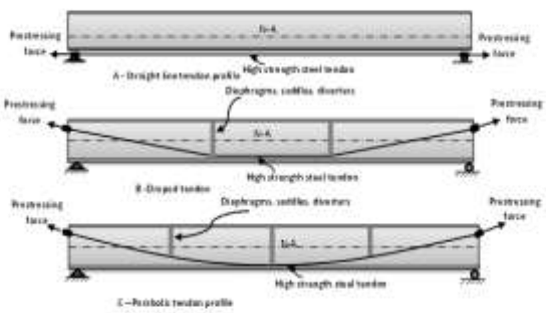


Figure (1) Strengthening by external high strength steel strands.

## 3. Research significance.

Steel structures have been used in the construction industry for centuries. Many modification and developments have been made to improve the performance of steel properties by adding a new material to the row material of steel manufactures. Engineers have found new mothed to improve of the original steel section strengths by external prestressing strand. The main objective of the work described in this study is to investigate and to get more information and more understanding about the flexure behavior of steel beams strengthening by external prestressing strands and compared with the reference steel beam.

## 4. Tested program

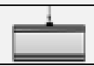
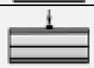
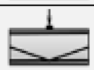
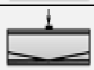
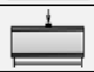
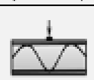
### 4.1 Description of specimens.

During the design phase of the experimental stages, the variable parameters included in this study are focused mainly on the existence of prestressing strands and layout of prestressing level (i.e. the eccentricity of the prestressing strand (e)). Six simply supported steel beams strengthening by external prestressing under one- point load and one reference beam without prestressing strands were tested. All specimens have the same I-section, two external prestressing strands of (12.7mm) diameter, the ends steel plate (25x125x250) mm and clear span length (2580) mm.

### 4.2 Specimens Identification and Retrofitting Schemes.

To identify the tested specimens with different retrofitting schemes, which it depending on different parameters such as amount of prestressing jacking stress and the layout of prestressing strands, the following system is used:
O: refers to the reference steel beam without any prestressing strand.
OX1X2X3X4: refers to the strengthened steel beam by prestressing strand.
Where
X1: refers to initial jacking stress ( $fpj$).
L= initial prestressing jacking stress of 815 MPa.
X2= eccentricity of prestressing strand at mid span
X3= eccentricity of prestressing strand at end span
X4= eccentricity of prestressing strand at critical effective depth for shear span
All definitions of samples are listed in Table (1).

**Table 1:** Description details of tested specimens

| Groups | Beams No. | Serial Symbols | Prestressing Strand Profile | Beams Shape | Eccentricity ($e$), (mm) | | |
|---|---|---|---|---|---|---|---|
| | | | | | $e_1$ | $e_2$ | $e_3$ |
| *1* | Ref. | O | ---- |  | ---- | ---- | ---- |
| 2 | 1 | OL000 | Straight with $e_1e_2e_3$ (000) |  | 0 | 0 | 0 |
| | 2 | OL101 | Draped with $e_1e_2e_3$(101) |  | 96 | 0 | 19.514 |
| | 3 | OL112 | Draped with $e_1e_2e_3$ (112) |  | 96 | 20 | 35.45 |
| | 4 | OL123 | Straight with $e_1e_2e_3$ (123) |  | 96 | 96 | 96 |
| | 5 | OL234 | Straight with $e_1e_2e_3$ (234) |  | 165 | 165 | 165 |
| | 6 | OL105 | Sinewave profile with $e_1e_2e_3$ (105) |  | 96 | 0 | -39 |

Where:-
$e_1$ = Eccentricity at mid span.
$e_2$ = Eccentricity at end span.
**$e_3$ = Eccentricity at effective depth for shear zone.**

### 4.3 Material properties of the test specimens and fabrication.

#### 4.3.1 Structural steel type

SS400 steel is one commonly hot rolled steel and used in the general structural element applications. SS400 is a material grade and designation defined in JIS G 3101 standard. JIS G 3101 is a Japanese material standard for hot Rolled steel plates, sheets, strips for general structural usage, according to this specification, the thickness for this SS400 material starts from 6 mm to 120 mm, the chemical composition of SS400 steels is listed in table (2), while the mechanical properties of SS400 Steel is listed in table (3) [7,8].

**Table 2:** Chemical Composition for SS400 Specification [7, 8]

| Grade | Min .Yielding Strength according to Thickness (MPa) | | Tensile strength, (MPa) | Elongation according to Thickness, (mm) | | | Min Impact resistance, (J) |
|---|---|---|---|---|---|---|---|
| | not over 16 mm | over 16 mm | | not over 5 mm | 5 to 16 mm | over 16 mm | |
| SS 400 | 245 | 235 | 400-510 | 21 | 17 | 19 | * |

#### 4.3.2 Structural steel section, fabrication and plate tests.

I-shape is a structural element which has a cross section forms the letter H and is the most widely used structural member. It is designed so that its flanges provide strength in a horizontal plane, while the web gives strength in a vertical plane. I-shapes are used as beams, columns, truss members, and in other load-bearing applications [9]. Hot rolled I-section (248x124) mm and with 25.7 kg/m mass per meter which it is manufactory in China and it used in this study. Table (4) shows geometrical details of steel section, while the end Steel plate of (25x125x250) mm can be welded directly to the steel beam by using welding process. The welds are 5 mm fillet welds made with E7018 electrodes. The end plates have two holes to allow to the prestressing strand to pass through them. End plate must be normally to the strand profile area as possible to reduce the stress concentration around the hole in the end plate and its can be problematic if the structural member is already under strength also local stiffeners may be required at end plate to prevent local buckling occur in the end plate [10]. The cutting process was conducted by using automaticity technique by using Computer Numerical Control (CNC) (ajan cnc) plasma machine to obtain exact design dimension and smooth cutting shapes.

Table (4) Dimension and properties of I- steel section [11]

| Size mm | Thickness mm | | Radius of curvature mm | Cross sectional area $mm^2 x 10^2$ | Mass per meter Kg/m | Moment of inertia $mm^4 x 10^4$ | | Radius of gyration mm | | Elastic section modulus $mm^3 x 10^3$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| H x B | t1 | t2 | r | A | | Ix | Iy | rx | ry | Sx | Sy |
| 248 x124 | 5 | 8 | 12 | 32.68 | 25.7 | 3540 | 255 | 104 | 27.9 | 285 | 41.1 |

The direct tension test was performed in the National Center for Constriction Laboratories and Research (NCCLR), the used machine for tests is (Zwick/Roell) universal hydraulic machine of (1200kN) capacity which used in testing direct tension steel symbols. The results of three specimens testing are listed in table (5) and the stress strain curve of the three specimens testing is shown in Fig. (2).

**Table 5:** Material properties of steel test symbols based on direct tension test

| Standards Specifications | Symbols No. | Min .Yielding Strength (Fy), MPa | Min. Ultimate Tensile strength (Fu), MPa | Total Elongation, % |
|---|---|---|---|---|
| NCCLR according to ASTM A36/ A36-2005 [11] | PL 10 | 356 | 524 | 25.2 |
| | PL 20 | 369 | 507 | 17.3 |
| | PL 30 | 360 | 507 | 15.9 |
| | Average value | 362 | 513 | 19.6 |
| American ASTM A36/ A36-2014 [12] | | ≥250 | ≥400 | ≥20 * |
| Japan of JIS G 3101 [7] | | ≥245 | ≥400 | ≥17 |
| Teste of results | | Conforming | Conforming | Conforming |

*=For wide flange shapes with flange thickness over (75 mm),the (550 MPa) maximum tensile strength does not applied and the minimum elongation of 19 % is applied [11,12]

So, one can be observed that all results value obtained from NCCLR were conforming to the technical standards specifications.

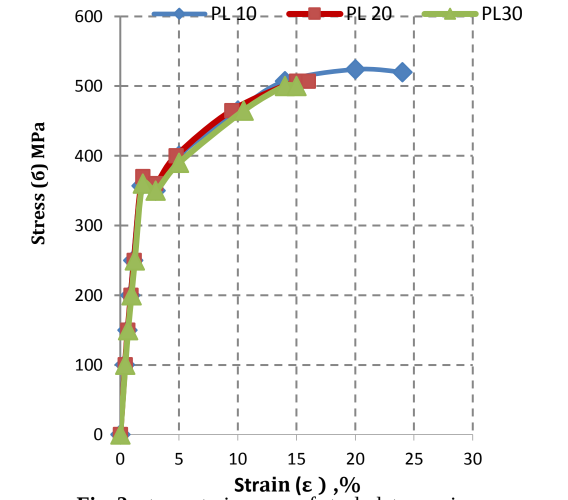



**Fig. 2:** stress strain curve of steel plate specimens

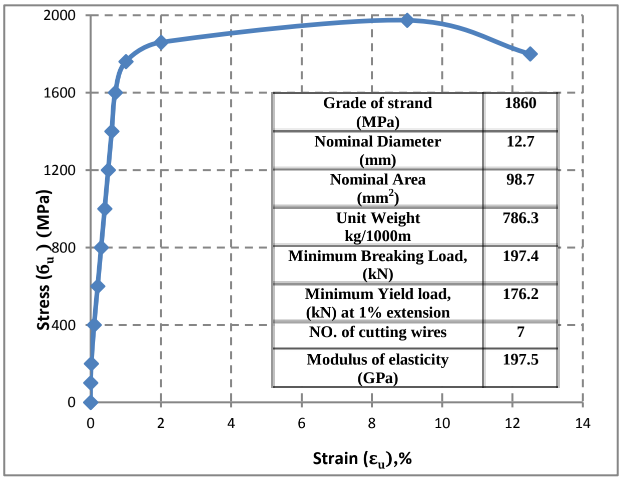
### 4.3.3 Prestressing Steel Strands

#### 4.3.3.1 Prestressing Steel Strands test.

Prestressing strand grade 270 low relaxation Seven-wire strands of (12.7mm) nominal diameter which manufactured by national meatal manufacturing and casting company (MAADANIYAH, Kingdom of Saudi Arabia) which used in this study. They strand was tested in the National Center for Constriction Laboratories and Research (NCCLR) and confirming to ASTM A416/ A416M-12a [13].The properties of the strand is shown in Fig. (3).

#### 4.3.3.2 Jacking stress applied.

The hydraulic machine consists of motor-driven hydraulic pump, hydraulic pipes attached to the four hydraulic jacks and to the single strand jack and measuring gauge to notice the applied pressure with (bar unit) which graduated from 0 to 600 bar, and the Prestressing level was applied at (200 bar) which its converted to 815 MPa, as shown in Fig.( 4).




| | |
|---|---|
| Grade of strand (MPa) | 1860 |
| Nominal Diameter (mm) | 12.7 |
| Nominal Area (mm$^2$) | 98.7 |
| Unit Weight kg/1000m | 786.3 |
| Minimum Breaking Load, (kN) | 197.4 |
| Minimum Yield load, (kN) at 1% extension | 176.2 |
| NO. of cutting wires | 7 |
| Modulus of elasticity (GPa) | 197.5 |

**Fig. 3:** stress -strain curve of grade 270 low relaxation seven wire strands at (12.7 mm) diameter

**Fig. 4:** Hydraulic machine and single strand jack prestressing strand.

### 4.4 Strain measurements in steel section.

Four channel TML data logger and switching box were used to monitor the strain during the applied load until to failure occurs. The strain gauges lie at mid span of tested beams, the reading of two strain gauges for flange were placed at top and bottom of the flange and lie at quarter length of flange width, while, the other two strain gauges for web are placed at top and bottom of the clear width of the web. The locations of strain gauges are shown in Fig. (5).

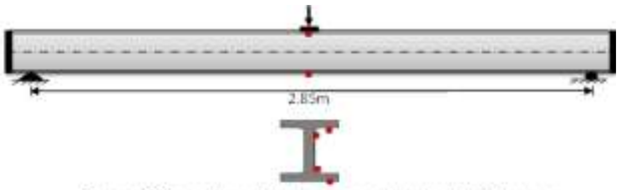



Figure (5) Location of strain gauges at typical steel beams

### 4.5 Load Measurements and Testing Procedure.

Tested steel beam were conducted in the Structural Laboratory of the Civil Engineering Department, at the College of Engineering, University of Al-Mustansiriyah. The used machine for tests is (MFL) universal hydraulic machine of (3000kN) capacity. Simply supported steel beams are tested under one concentrated point load at mid span, steel beam are placed with clear span of (2850mm). Steel bearing plate (12x100) mm is used to convert the applied load to line load over the steel beam surface. During testing time, steel beam is placed over supports; deflection dial gauges of (0.01 mm) accuracy with (30 mm) capacity are fixed in the designated locations at mid and quarter span. All dial gauges were rested to zero. Load of (5kN) is applied and removed in order to recheck the zero readings. All the tests are carried out under load step of (2kN) and measurements are taken at each (10kN) increment, strain gauges reading and dial gauges are taken at each increment. Measurements are recorded until the failure of steel beams at which the applied load is drop with increasing deformation, the test machine and instrumentation details show in Fig.(6)

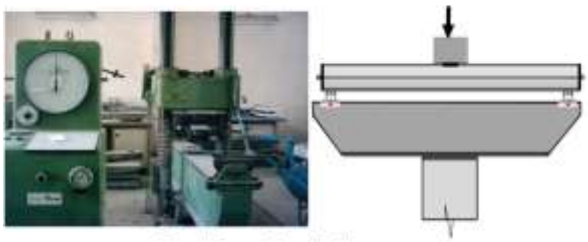


Figure (6) Test machine and loading arrangements

# 5. Experimental parametric studies.

The tested beams are divided into two categories according to existing of external prestressing strands, the first category consists of one steel beam as a reference, while, the second group deals with steel beams strengthening by external prestressing strands consists of six steel beams divided according to the eccentricity location of prestressing strand (e) ranging from (0 to 165) mm with jacking stress ($fpj$ = 815 MPa). This experimental study has been carried out to investigate the effect of eccentricity location on the flexural behaviors of steel beams strengthening by external prestressing strand under one point load. The experimental flexural strains for tested beams were monitored through four channels be arranged at mid span of tested beams during to applied load until to failure occurs, the strains of flange were recorded by using strain gauge placed at top and bottom of the flange distribute at distance of quarter length of the flange width. Full experimental results of tested beams are illustrated in table (6).

**Table 6**: Experimental flexural results of tested beams

| Groups | Beams No*. | Series Sym-bols | Ultimate moment applied Exp. (Mu), (kN.m) | Max. curvature at mid span locations($\varphi_{exp}$) (1/mm x $10^{-6}$) at | |
|---|---|---|---|---|---|
| | | | | Top flange | Bottom flange |
| 1 | Ref. | O | 204.843 | 107.922 | 134.750 |
| 2 | 1 | OL000 | 205.200 | 87.068 | 77.669 |
| | 2 | OL101 | 258.281 | 152.235 | 23.679 |
| | 3 | OL112 | 272.531 | 169.864 | 45.412 |
| | 4 | OL123 | 232.987 | 76.798 | 52.147 |
| | 5 | OL234 | 347.343 | 102.467 | 35.905 |
| | 6 | OL105 | 304.237 | 147.710 | 29.297 |

## 5.1 Moment curvature response.

In order to investigate the effect of the locations of eccentricity on the flexural behavior of tested beams, the beams are divided into two groups according to jacking stress ($fpj$). Each group was subdivided into six beams tested at different location of eccentricity ranging from (0 to 165) mm at constant jacking stress($fpj$).During the test, it can be observed that the moment curvature curves for tested beams strengthening with external prestressing strand are stiffer and with less ductility as compare with the reference beam and the percentage of stiffening increase with increasing the eccentricity locations. This is due to axial force that generated from existing of external prestressing strand which improved the web resistance and bottom flange and it's also contribute to resist the applied load, as shown in Fig.(7) and Fig.(8).

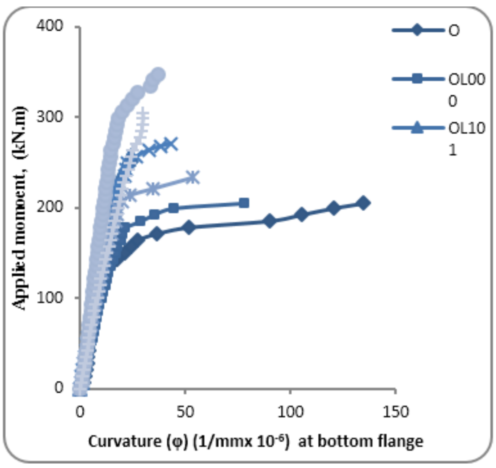



**Fig. 7:** Effect of eccentricity location of prestressing strand on the moment curvature curves at bottom flange of tested beams under one point load.

## 5.2. Moment capacity of the tested beams.

To study the influence of eccentricity locations on the ultimate moment capacity of the tested beams, the beams were tested at different location of eccentricity changed from (0 to 165) mm. During the tests, it was found that the maximum applied moment increase to 0.1739%, 26.086%, 33.043%, 48.521%, 13.739% and 69.565% with increasing the eccentricity location from (0 to 165) mm respectively as compare with the reference beam, that as a result of provided initial moment due to prestressing force which has effect vice versa moment that generated due to applied load as listed in table (7). The increasing percentage in ultimate moment capacity of tested beams is shown in Fig. (9) and Fig (10). So, one can be observed that the maximum applied load increase with increasing the eccentricity locations that due to exist of external prestressing strand which improved the web resistance and bottom flange and it's also contributed with the steel beams to resist the applied load.

**Table 7:** Ultimate moment capacity of tested beams

| Beams No. | Series Symbols | Jacking Stress, ($fp_j$) (MPa) | Ultimate moment capacity,(Mu), (kN.m) | Percentage increasing in moment capacity, (%),as compare with reference |
|---|---|---|---|---|
| Ref. | O | ------- | 204.843 | 0 |
| 1 | OL000 | 815 | 205.200 | 0.173 |
| 2 | OL101 | 815 | 258.281 | 26.086 |
| 3 | OL112 | 815 | 272.531 | 33.043 |
| 4 | OL123 | 815 | 232.987 | 13.739 |
| 5 | OL234 | 815 | 347.343 | 69.565 |
| 6 | OL105 | 815 | 304.237 | 48.521 |

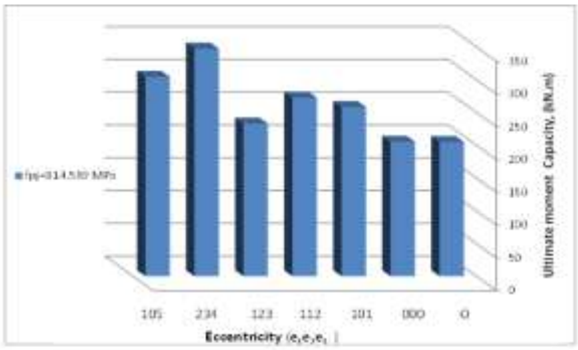



Figure (9) Ultimate moment capacity of tested beams at different values of eccentricity and jacking stress

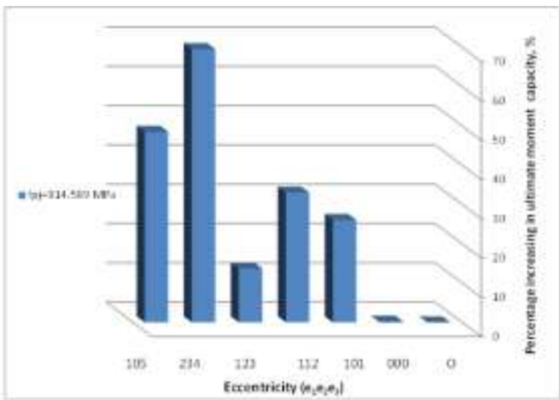



Figure (10) Percentages increase in ultimate moment capacity of tested beams at different values of eccentricity and jacking stress as compare with the reference

## 5.3 Radius of curvature at top flange of tested beams.

In order to understand the influence of eccentricity location on the radius of curvature of the tested beams, the beams were tested at different location of eccentricity ranging from (0 to 165) mm at jacking stress (fpj=814.589 MPa). During the tests, the percentage increase in the maximum radius of curvature at top flange for steel beams change to-19.323%, 41.06%, 57.395%, 36.867%, -28.829% and -5.054% with increase the eccentricity location from (0 to 165) mm respectively as compare with the reference beam. So one can be observed that the radius of curvatures at top flange increase with increase the eccentricity location from (0 to 165) mm, on the other hand the negative sing in the percentage increasing explain the decreasing in radius of curvatures as result of local buckling in top region and that lead to failure occur immediately failure, as listed in table (8). The percentage increase in maximum radius of curvature at top flange for tested beams is shown in Fig.(11).

**Table (8)** Percentage increasing in maximum experimental curvature at top flange for tested beams

| Beams No. | Series Symbols | Jacking Stress,($fp_j$) (MPa) | Maximum exp. Curvature ($\varphi_{exp}$) at top flange | Percentage increasing in maximum curvature ($\varphi_{exp}$) at top flange, (%) |
|---|---|---|---|---|
| Ref. | O | ------- | 107.922 | 0 |
| 1 | OL000 | 815 | 87.068 | -19.323 |
| 2 | OL101 | 815 | 152.235 | 41.060 |
| 3 | OL112 | 815 | 169.864 | 57.395 |
| 4 | OL123 | 815 | 76.798 | -28.839 |
| 5 | OL234 | 815 | 102.467 | -5.054 |
| 6 | OL105 | 815 | 147.71 | 36.867 |

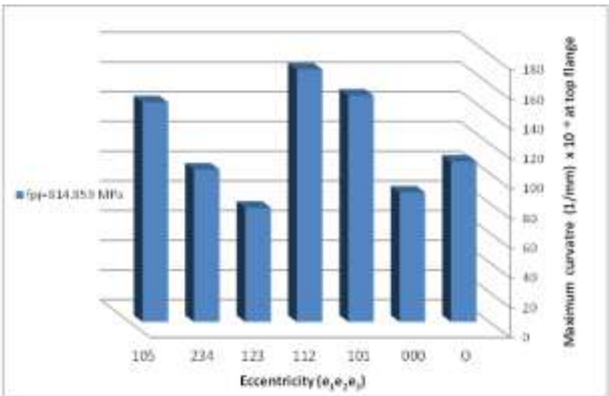



Figure (11) Maximum radius of curvatures of tested beams at different values of eccentricity and jacking stress

### 5.4 Radius of curvature at bottom flange of tested beams.

In order to understand the influence of eccentricity location on the radius of curvature of the tested beams, the beams were tested at different location of eccentricity ranging from (0 to 165) mm at constant jacking stress (fpj). During the tests, the increasing percentage in maximum radius of curvatures at bottom flange of tested beams decrease to 42.360%, 82.427%, 66.299%, 78.258%, 61.301% and 73.354% with increase the eccentricity location from (0 to 165) mm respectively at jacking stress (fpj=814.589 MPa) as compare with the reference beam, as listed in table (9). The decreasing percentage in maximum radius of curvatures at bottom flange of tested beams is shown in Fig.(12) and Fig.(13). So, one can be observed that the maximum radius of curvature at bottom flange were decreased with increasing the eccentricity locations at mid span with constant jacking stress (fpj) that due to exist of external prestressing strand which improved the web resistance and bottom flange and it's also contributed with the steel beams to resist the applied load.

**Table 9:** Maximum experimental curvature at bottom flange of tested beams

| Beams No. | Series Symbols | Jacking Stress, ($fp_j$) (MPa) | Maximum exp. Curvature ($\varphi_{exp}$) at bottom flange, (1/mm)x$10^{-6}$ | Percentage increasing in maximum curvature ($\varphi_{exp}$) at bottom flange, (%) |
|---|---|---|---|---|
| Ref. | O | ------- | 134.750 | 0 |
| 1 | OL000 | 815 | 77.669 | -42.360 |
| 2 | OL101 | 815 | 23.679 | -82.427 |
| 3 | OL112 | 815 | 45.412 | -66.299 |
| 4 | OL123 | 815 | 52.147 | -61.301 |
| 5 | OL234 | 815 | 35.905 | -73.354 |
| 6 | OL105 | 815 | 29.297 | -78.258 |

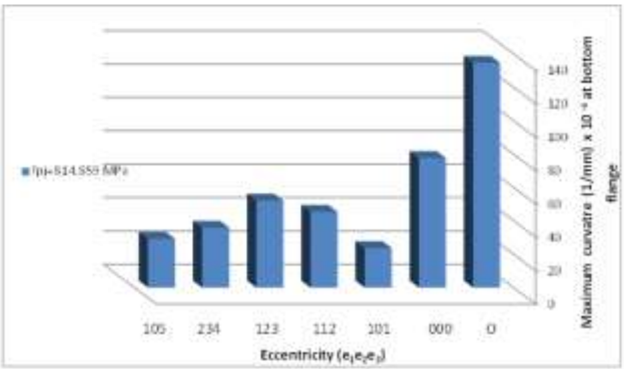



Figure (12) Maximum radius of curvatures of tested beams at different values of eccentricity and jacking stress

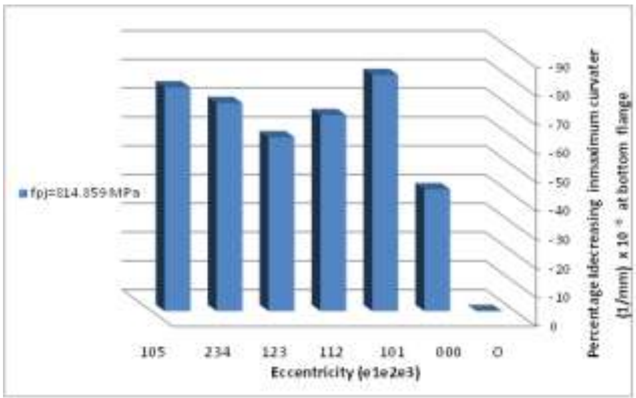



Figure (13) Percentage increasing in maximum radius of curvature of tested beams at different values of eccentricity and jacking stress as compare with a reference

## 6. Conclusions.

Based on the tested beams results of this experimental investigation on the deflection behavior of steel beams strengthening by prestressing strands, the following conclusions are drawn.

1. Behavior of moment curvature for the tested beams are stiffer and less ductility than the reference beams and the percentage of stiffening increase with increase the jacking stress ($fpj$) at constant eccentricity (e).
2. The ultimate moment capacity increase to 0.173%, 26.086%, 33.043%,48.521%, 13.739% and 69.565% with increase the eccentricity location from (0 to 165) mm respectively at jacking stress ($fpj$=814.589 MPa) as compare with the reference beam.
3. The maximum radius of curvature at top flange change to -19.323%, 41.06%, 57.395%, 36.867%, -28.829% and -5.054% with increase the eccentricity location from (0 to 165) mm respectively at jacking stress ($fpj$=814.589 MPa) as compare with the reference beam. So the radius of curvatures at top flange increase with increase the eccentricity location from (0 to 165) mm until buckling occurs in top region and that lead to failure occur immediately failure which explain the decreasing in radius of curvatures.
4. The maximum radius of curvature at bottom flange decrease to 42.360%, 82.427%, 66.299%, 78.258%, 61.301% and 73.354% with increase the eccentricity location from (0 to 165) mm respectively at jacking stress ($fpj$=814.589 MPa) as com-

pare with the reference beam. So the maximum radius of curvature at bottom flange were decreased with increasing the eccentricity locations at mid span with constant jacking stress ($fpj$) that due to exist of external prestressing strand which improved the web resistance and bottom flange and it's also contributed with the steel beams to resist the applied load.

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