Effect of external prestressing strands on the Yielding Stage behaviours of steel beams

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Abstract. Seven steel beams were tested under one point load to investigate the effect of existence of external prestressing strands on the behavior of steel beams at yielding stage. All steel beams have the same gross area, overall length and the strengthened specimens are employed by two low relaxation strands. The steel beams are divided into two groups according to existence of prestressing strands, the first group involves one steel beam which is considered as a reference beam, while, the second group involves six specimens divided according to the location of prestressing strand (e) at jacking stress (fρj =1120.061 MPa). During the tests, it can be noted that the load strain response for strengthened steel beams are stiffer and the increasing percent of stiffening increases with the increasing of strand eccentricity and the maximum yielding load of strengthened tested beams increases with the increasing of strand eccentricity and the maximum enhancement in yielding load of strengthened tested beams reaches to 126.331% in the OM234 sample compared with the reference beam. Also, it was found that the yielding strain positions changed from bottom flange to the top region for the strengthened tested beams as compared with the reference steel beam and the increasing percent in the yielding to ultimate load ratio (Py/Pu) for the strengthened tested beams increases with the increasing of strand eccentricity at constant applied jacking stress. The maximum percentage increase in yielding to ultimate load ratio (Py/Pu) of strengthened tested beams reaches to 21.06% in the Straight strand profile as defined by OM234 sample as compared with the reference beam.

1. Introduction

The most important properties of steel are great durability and formability, good yielding, tensile strength and thermal conductivity, so steel is considerably the most useful material for building structures with strength of approximately ten times that of concrete that is due to its high ductility, uniform and homogeneous properties, high strength to weight ratio, high elastic modules, high amount of energy absorption in seismic action, can be easily recycled, quicker to fabricate and erect. Because of the low self-weight, the dimension of steel frame can be reduced [1]. Creating permanent stress in the steel member in order to develop resistance against applied service load is called as prestressing. Prestressing is a wonderful method to introduce an internal stress in steel sections to counter balance stresses caused by external loads so as to improve the performance and durability of steel members [2, 3].

2. External Prestressing.
External prestressing is a posttension method in which the external prestressing strands are put on the exterior of a steel section and the prestressing force is transferred to the steel sections within anchorages plates and diverters. It is adopted for strength and rehabilitation of old important members, usually it is used for strengthening buildings and bridges at fatigue state and over expected loading design [4]. The model of external prestressing in steel beams can be achieved by anchoring high strength strand at the two ends of steel beams through end steel plate. The external prestressing strand shape can be placed on the interior length by an indefinite number of diverters which prevents slipping in the external prestressing strand and helps to give the scheme profile shape as a straight, draped or parabolic depending on the loading applied and bending moment diagrams [5] as shown in Figure (1), then the strand was tensioned at the same time from one end by using equal jacking force to pull-out the external prestressing strands. Superior attention must be adopted to balance the jacking force in the external prestressing strands to prevent the biaxial bending and distortion of the tested beam [8].

![Diagram](image-url)

**Figure 1.** Strengthening of steel beams by external high strength steel strands.

### 3. Research Significance.
The aim of this work is to understand and to get more information about the yielding strength behaviour of steel beams strengthened by external prestressing strands at different eccentricity locations.

### 4. Experimental program.
#### 4.1 Description of Specimens.
The variable parameters involved in this research are concentrated on the existence of external prestressing strands and arrangement of prestressing level (i.e. the eccentricity of the external prestressing strand (e)). Seven steel beams under one point load are tested and six specimens are strengthened by external prestressing. All samples have same I-section (H248x124) mm; ends steel plate (25x125x250) mm, clear span length (2850) mm and the strengthening was achieved by two external prestressing strands of (12.7mm) diameter.

#### 4.2 Specimens classifications.
To classify the tested samples which depending on the arrangement of external prestressing strands and jacking stress, the following classification is used: (OMX;X$_1$X$_2$)

- **O:** for original reference steel
- **OM:** strengthening beam under 1120MPa initial jacking stress
- **X$_1$:** eccentricity of external prestressing strands at mid span, defined by 0, 1 and 2
X₂: eccentricity of external prestressing strands at end span, defined by 0, 1, 2 and 3
X₃: eccentricity of external prestressing strands at critical effective depth for shear span, defined by 0, 1, 2, 3, 4 and 5

All the details of tested specimens are shown in Figure 2, while Table 1 illustrates the specimen identification system.

![Figure 2. Details of tested beams](image)

**Table 1** Description details of tested specimens

| Groups | Beams No. | Serial Symbols | Prestressing Strand Profile | Beams Shape | Jacking Stress(fpj), MPa | Eccentricity of prestressing strands(e), (mm) |
|--------|-----------|----------------|-----------------------------|-------------|------------------------|---------------------------------|
|        |           |                |                             |             |                        | e₁  e₂  e₃                        |
| 1      | Ref.      | O              | ****                        | ****        | 1120.061               | 0  0  0                         |
| 2      | OM000     | Straight with e₁e₂e₃ (000) |                     | 1120.061 | 0  0  0                  |
| 3      | OM101     | Draped with e₁e₂e₃ (101)  |                     | 1120.061 | 96  0  19.514           |
| 4      | OM112     | Draped with e₁e₂e₃ (112)  |                     | 1120.061 | 96  20  35.45           |
| 5      | OM123     | Straight with e₁e₂e₃ (123) |                     | 1120.061 | 96  96  96              |
| 6      | OM234     | Straight with e₁e₂e₃ (234) |                     | 1120.061 | 165  165  165           |
| 7      | OM105     | Sinewave profile with e₁e₂e₃ (105) |                     | 1120.061 | 96  0  -39              |
4.3 Material Properties and fabrications.

4.3.1 Steel Section Type. Hot rolled steel section, (H248x124) with (25.7kg/m) mass per meter of SS400 is defined in JIS G 3101 standard in this study [7], [8].

4.3.2 Fabrication of samples and Plate Tests. End steel plates welded with H248x124 with 5mm fillet welds made with E7018 electrodes to provide fixity of prestressing wedge anchored. End plate must be perpendicular to the external prestressing strands profile area as much as possible in order to reduce the stress concentration around the hole in the end plates and it can be problematic if the structural member is under strength also local stiffeners may be required at end plate to prevent local buckling which may occur in the end plate [10]. The test of direct tension was achieved in the National Centre for Constriction Laboratories and Research (NCCLR). The stress strain curve of the three samples is shown in Figure 3 and the adopted values which are used in this study are illustrated in Table 2 and the results of three specimen tests are listed in Table 3.

| Material properties | Ultimate Tensile strength (fu), (MPa) | Max. strain at yielding stage (εy) x10-6 | Yielding Strength(Fy), (MPa) | Modulus of elasticity (GPa) |
|---------------------|-------------------------------------|---------------------------------|-------------------------------|--------------------------|
| Adopted value       | 513                                 | 1810                            | 362                           | 200                      |

| Standards Specifications | Symbols No. | Min. Yielding Strength(Fy), MPa | Min. Ultimate Tensile strength (fu), MPa | Total Elongation, % |
|--------------------------|-------------|---------------------------------|------------------------------------------|---------------------|
| NCCLR Tested Results     | PL 10       | 356                             | 524                                       | 23.2                |
|                          | PL 20       | 369                             | 507                                       | 20.5                |
|                          | PL 30       | 360                             | 507                                       | 18.9                |
|                          | Average value | 362                     | 513                                       | 20.87               |
| American ASTM A36/ A362014[13] |         | 250≥                           | 400≥                                     | 20 ≥                 |
| Japan of JIS G 3101[7]   |         | 245≥                           | 400≥                                     | 17 ≥                 |

4.3.3 Prestressing Steel Strands.

4.3.3.1 Testing of Prestressing Strands. Seven-wire strands of (12.7mm) nominal diameter and Prestressing strand of grade 270 low relaxation which was produced by national metal manufacturing and casting company (MAADANIYAH, Kingdom of Saudi Arabia) is used in this study. The strand was tested in the (NCCLR) and verifying to ASTM A416/ A416M-12a [13]. The properties of the prestressing strand are presented in Figure 4.
4.3.3.2 Jacking Stress Applied.
Two of Seven-wire strands of (12.7mm) nominal diameter and Prestressing strand of grade 270 low relaxation were selected and arranged at eccentricity location varying from (0 to 165)mm through the longitudinal axis of the steel beams. Prestressing level was applied at (275) bar, the prestressing stress converter was from (bar) to (1120.06 MPa). The hydraulic machine which was used is shown in Figure 5.

4.4 Strain Monitoring in Steel Samples.
The experimental shear strains for steel beams were observed by four strain gauges placed at mid span of steel beams, the reading of two strain gauges for flange is placed at top and bottom of the flanges and placed on the 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 positions of strain gauges are illustrated in Figure 6.

5. Experimental Works.
Seven steel beams have been tested under one point load with simply supported span to investigate the yielding stage strength behaviour of steel beams strengthened with external prestressing strands. All the tested beams have the same gross section area, with effective length of (2850) mm and strengthened by two external prestressing strands with (12.7mm) diameter. The tested beams are divided into two groups according to existence of external prestressing strands, the first group 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 (e) ranging from (0 to 165) mm. Full experimental yielding outcomes of the tested beams are illustrated in Table 4 as follows:-

Table 4 Experimental strain results of steel beams at yielding stage

| Groups | Beams No. | Series Symbols | Maximum applied load (P_u), (kN) | Exp. Yielding load, (P_y), (kN) | Max. Exp. strain at mid span at yield stages (ε_y × 10^-6) |
|--------|-----------|----------------|-------------------------------|------------------------|-----------------------------------|
|        |           |                | Top flange | Bottom flange | Top of web | Bottom of web |
| 1      | Ref. O    | 287.5          | 191.674    | -1357          | 1810        | -935          | 1539        |
| 1      | OM000     | 289            | 201.371    | -1550          | 1761        | -1810         | 1500        |
| 2      | OM101     | 372.5          | 257.140    | -1810          | 1412        | -1300         | 1050        |
| 3      | OM112     | 397.5          | 295.175    | -1810          | 1764        | -1648         | 975         |
| 4      | OM123     | 357.5          | 266.451    | -1810          | 1507        | -1539         | 1091        |
| 5      | OM234     | 537.5          | 433.818    | -1810          | 1590        | -1456         | 1518        |
| 6      | OM105     | 465            | 316.045    | -1679          | 1573        | -1810         | 1356        |

5.1 Load Strain Response.
Based on the tests, it can be seen that the load strain curves for steel beams strengthened by external prestressing strands were stiffer at top and bottom region due to existence of external prestressing strand which improved the web and bottom flange resistance and it's also contributed with the steel beams to resist the applied load as compared with the reference beam. Also the percentage of stiffening increases with increasing the eccentricity locations as shown in figure 7.

5.2. Yielding Load of the Tested Beams.
During the tests it was found that the yielding load increases to 5.059%, 32.067%, 53.998%, 64.886%, 37.969% and 126.331% when the eccentricity position changed from (0 to 165) mm, respectively as compared with the reference beam. On the other hand, it can be observed that the percentage of increase in yielding load to ultimate load ratio (P_y/P_u) increased about (4.513%, 1.931%, 11.382%, 1.946%, 10.594% and 21.06%) when the eccentricity position change from (0 to 165) mm, respectively as compared with the reference beam. So, it can be seen that the load at yielding stage and the increase in percentage in yielding load to ultimate load (P_y/P_u) increases with increasing of the eccentricity locations under constant jacking stress(fpj). The percentage of increase in the yielding load and the percentage increase in yielding load to ultimate load (P_y/P_u) of steel beams are shown in Table 5 and Figure 8.
**Figure 7.** Effect of eccentricity location of prestressing strand on the applied load - strain relationship for tested beams

**Table 5.** Experimental result of ultimate and yielding load of tested beams

| Beams No. | Series Symbols | Ultimate Exp. Applied load, \( (P_u) \) (kN) | Percentage of increase in ultimate load \( (P_u) \), (kN) as compared with reference beam | Yielding Exp. load, \( (P_y) \), (kN.) | Percentage of increase in yielding load as compared with reference beam, (%) | Yielding load to ultimate load ratio \( (P_y/P_u) \),\% | Percentage of increase in yielding load to ultimate load ratio \( (P_y/P_u) \) as compared with reference beam,\% |
|-----------|----------------|---------------------------------|-----------------------------------------------------------------|--------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 1         | O              | 287.5                           | 0                                                               | 191.674                       | 0                               | 66.669                          | 0                               |
| 2         | OM000          | 289                             | 0.521                                                           | 201.371                       | 5.059                           | 69.678                          | 4.513                           |
| 3         | OM101          | 372.5                           | 29.565                                                          | 257.140                       | 34.154                          | 69.030                          | 3.542                           |
| 4         | OM112          | 397.5                           | 29.565                                                          | 295.175                       | 53.998                          | 74.257                          | 11.382                          |
| 5         | OM123          | 357.5                           | 24.347                                                          | 266.451                       | 39.012                          | 74.531                          | 11.793                          |
| 6         | OM234          | 537.5                           | 86.956                                                          | 433.818                       | 126.331                         | 80.710                          | 21.060                          |
| 7         | OM105          | 465                             | 61.739                                                          | 316.045                       | 64.886                          | 67.966                          | 1.9460                          |
5.3. Yielding Strain of the Tested Beams.
During the tests it was found that the yielding strain positions of strengthening beams changed from bottom flange to the top region as compared with the reference beam. That is due to the existence of external prestressing strand, which improves the bottom and top flange also, it improves the web resistance under applied load, as shown in Table 6. During the tests, it was found that the percentage of increase in yielding strain in top flange increases to 14.222%, 33.382%, 33.382%, 23.728%, 33.382%, and 17.17% with increasing of the eccentricity location from (0 to 165) mm, respectively as compared with the reference beam, while the increase in percentage in yielding strain in bottom flange decreases to 2.707%, 21.989%, 2.541%, 13.093%, 16.74%, and 0% with increasing of the eccentricity location from (0 to 165) mm, respectively compared with the reference beam. On the other hand, the increasing percentage in yielding strain in top web increased to 93.582%, 39.037%, 76.256%, 93.582%, 64.598%, and 55.582% with increasing of the eccentricity location from (0 to 165) mm, respectively compared with the reference beam, while the increasing percentage in yielding strain in bottom web decreases to 2.534%, 31.773%, 36.647%, 11.89%, 29.109 %, and 1.364 % with increasing of the eccentricity location from (0 to 165) mm, respectively compared with the reference beam.

| Table 6. Experimental results of strain in mid span at yielding stag and increasing percentage in yielding strain of tested beams |
|---|---|---|---|---|---|---|---|
| Series Symbols | Exp. Strain and percentage increase in strain at mid span locations at yielding stages | | | | | | |
| | Top flange | Percentage increase in top flange, % | Bottom flange | Percentage increase in bottom flange, % | Top of web | Percentage increase in top of web, % | Bottom of web | Percentage increase in bottom of web, % | First yielding segment part location |
| O | -1357 | 0 | 1810 | 0 | -935 | 0 | 1539 | 0 | Bottom flange |
| OM000 | -1550 | 14.222 | 1761 | -2.707 | -1810 | 93.582 | 1500 | -2.534 | Top of web |
| OM101 | -1810 | 33.382 | 1412 | -21.989 | -1300 | 39.037 | 1050 | -31.773 | Top flange |
| OM112 | -1810 | 33.382 | 1764 | -2.541 | -1648 | 76.256 | 975 | -36.647 | Top flange |
| OM123 | -1810 | 33.382 | 1507 | -16.740 | -1539 | 64.598 | 1091 | -29.109 | Top flange |
| OM234 | -1590 | 17.170 | 1810 | 0 | -1456 | 55.721 | 1518 | -1.364 | Top flange |
| OM105 | -1679 | 23.728 | 1573 | -13.093 | -1810 | 93.582 | 1356 | -11.890 | Top of web |

6. Conclusions
During the experimental investigation on the yielding behaviour of steel beams strengthened by external prestressing strands, the following conclusions are drawn:

1. The load strain curves for strengthened tested beams are stiffer as compared with the reference beam and the percentage of stiffening increases with the increasing of strand eccentricity.
2. The yielding strain positions changed from bottom flange to the top region for the strengthened tested beams as compared with the reference beam.
3. The percentage of increase in yielding to ultimate load ratio \( P_y/P_u \) for the strengthened tested beams increases with the increase in strand eccentricity at constant applied jacking stress. The maximum percentage increase in yielding to ultimate load ratio \( P_y/P_u \) of strengthened tested.
beams reaches to 21.06% in the Straight strand profile as defined by OM234 sample as compared with the reference beam.

4. The percentage of increase in strain in top flange in the yielding stage for strengthened tested beams increases with the increase in strand eccentricity. The maximum percentage of increase in yielding strain in top flange of strengthened tested beams reaches to 33.382% in the OM101, OM112 and OM123 samples as compared with the reference beam.

5. The increase in percentage in strain in bottom flange in the yielding stage for strengthened tested beams decreases with the increase in strand eccentricity. The maximum percentage of decrease in yielding strain in bottom flange of strengthened tested beams reaches to 21.989% in the OM101 sample as compared with the reference beam.

6. The increase in percentage in strain in top of web in the yielding stage for the strengthened tested beams increases with the increase in strand eccentricity. The maximum percentage of increase in yielding strain in top of web of strengthened tested beams reaches to 93.582% in the OM000 and OM105 samples as compared with the reference beam.

7. The increase in percentage in strain in bottom of web in the yielding stage for strengthened tested beams decreases with the increase in strand eccentricity. The maximum percentage of decrease in yielding strain in bottom of web of strengthened tested beams reaches to 36.647% in the OM112 sample as compared with the reference beam.

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