The Effect of Prestressing Strands on the Shear Behaviours of Steel Beams

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Abstract. Seven simply supported steel beams were tested to examine the effects, in terms of strengthening, of external prestressing of strands on the shear behaviour of steel beams. All beams had the same steel section and clear span length and strengthening was implemented using two external prestressing strands. The tested beams were divided into two groups based on the presence of the external prestressing strands: the first group thus consisted of just one steel beam, as a reference, while, the second group had six steel beams strengthened by external prestressing strands divided according to the eccentricity location of a prestressing strand with jacking stress \( f_p j = 1120.061 \, MPa \). During the tests, it was found that the shear load strain curves for the tested beams were slightly stiffer than for the reference beams and that the percentage of stiffening increased with any increase in the eccentricity of strand locations from the shear points; the maximum shear load increased by 0.521\%, 29.565\%, 38.26\%, 61.739\%, 24.347\% and 86.956\% with an increases in the eccentricity location from (0 to 165) mm compared to the reference beam. The maximum shear strain increased by 9.664\%, 3.553\%, 8.121\%, 62.436\%, 37.563\% and 13.451\% with an increase in the eccentricity location from (0 to 165) mm respectively as compared with the reference beam.

1. Introduction
The most important properties of steel are its durability formability, yielding nature, tensile strength, and thermal conductivity; based on these, steel is clearly the most useful material for building structures, as well as having a strength approximately ten times that of concrete that due to its toughness and homogeneous properties [1]. Producing permanent stress in a structural member to improve resistance against service loads is called applying prestress or prestressing and its aim to generate internal stress in structural members to counterbalance stresses caused by external loads to enhance performance and durability of the structural members [2, 3].

2. External prestressing.
External prestressing is a posttension method in which external prestressing strands are put on the exterior of a steel section so that prestressing forces are transferred to the steel sections via anchorages plates and diverters. It is an adopted to strengthen and rehabilitate older but still important members, and as such, it is usually used for strengthening buildings and bridges that are at fatigue state or over

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their expected loading design [4]. A model of external prestressing in steel beams can be achieved by anchoring high strength strands at the two ends of a steel beam by means of a steel end plate. The external prestressing strand is then placed on the interior length by any number of diverters which try to prevent slipping in the external prestressing strand and help to give the scheme profile the correct shape, a whether straight, draped, or and parabolic, depending on the loading applied. Bending moment [5] as shown in the diagrams in Fig.1 is thus produced, then the strand is tensioned at the same time from ends by using of equal jacking force to pull the external prestressing strands. Keen attention must be paid to balancing the jacking force in the external prestressing strands to prevent biaxial bending and distortion of the tested beam [6].

![Diagram](image_url)

**Figure 1.** Strengthening using external high strength steel

3. **Research significance.**

The aim of this work is to study and understand the effect of prestressing strand on the shear behaviours of steel beams strengthened by external prestressing strands at different eccentricities at constant jacking stress.

4. **Test programme.**

4.1. **Description of specimens.**

The variable parameters involved in this research focus on the existence of external prestressing strands and the arrangement of prestressing levels (based on the eccentricity of the external prestressing strand (e)). Seven steel beams under one-point loads were tested with six specimens being strengthened by external prestressing. All samples had the same I-section; ends steel plates of 25x125x250 mm, and clear span lengths of 2850 mm; strengthening was achieved by applying two external prestressing strands each of (12.7mm) diameter.

4.2. **Specimens Identification.**

To identify the tested specimens: the following system was used:
- O, M, X1, X2, X3

  Where:-
  - O: original reference steel
  - OM: strengthening beam under 1120MPa initial jacking stress
  - X1: 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 sample definitions are listed in the flow-chart shown in Fig. 2 and the Table. 1 show the specimen identification system used based on the specimen identification pattern described. The details of test specimens are shown in Fig. 3.

**Table 1 Description details of tested specimens**

| Groups | Beams No. | Serial Symbols | Prestressing Strand Profile | Jacking Stress \((f_{pj})\), MPa | Eccentricity \((e)\), (mm) |
|--------|-----------|----------------|-------------------------------|---------------------------------|--------------------------|
|        |           |                |                               |                                 | \(e_1^*\) \(e_2^{**}\) \(e_3^{***}\) |
| 1      | Ref.      | O              | ----                          | ----                            | ---- ---- ---- ---- |
| 1      | OM000     | Straight with \(e_1e_2e_3\) (000) | 1120.061                      | 0 0 0                           |
| 2      | OM101     | Draped with \(e_1e_2e_3\) (101) | 1120.061                      | 96 0 19.514                     |
| 3      | OM112     | Draped with \(e_1e_2e_3\) (112) | 1120.061                      | 96 20 35.45                     |
| 4      | OM123     | Straight with \(e_1e_2e_3\) (123) | 1120.061                      | 96 96 96                        |
| 5      | OM234     | Straight with \(e_1e_2e_3\) (234) | 1120.061                      | 165 165 165                     |
| 6      | OM105     | Sine wave profile with \(e_1e_2e_3\) (105) | 1120.061                      | 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.

**Figure 2** Flow chart of the experimental details of tested beams
4.3 Material properties and fabrication of the test specimens.

4.3.1 Structural steel type.
SS400 steel is a hot rolled steel used in structural applications defined in Japanese material standard for hot rolled steel plates, sheets, and strips (JIS G 3101). The dimension and properties of steel sections used in this study are listed in Table 2. [7, 8]

![Figure 3](image)

**Figure 3** Details of tested beams

| Table 2 | Dimension and properties of steel section [8] |
|---------|---------------------------------------------|
| 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$^4$ | Radius of gyration mm | Elastic section modulus mm$^3$ x 10$^3$ |
| H x B   | t1  | t2  | r   | A   | $I_x$ | $I_y$ | rx   | ry   | Sx  | Sy  |
| 248 x 124 | 5  | 8  | 12  | 32.68 | 25.7  | 255  | 104  | 27.9 | 285 | 41.1 |
4.3.2. Fabrication of samples and Plate Tests

End steel plates and H248x124 were welded on with 5mm fillet welds made with E7018 electrodes to allow the passing and fixing of strands. End plates must be as perpendicular to the external prestressing strands profile area as possible in order to reduce the stress concentration around the hole in the end plates; this can be problematic if the structural member is under strength, and local stiffeners may be required at end plate to prevent local buckling [9]. The representative test of direct tension was done at the National Centre for Constriction Laboratories and Research (NCCLR). The stress strain curve of the three samples is shown in Fig. 4 and the results of three specimens tests are listed in Table 3.

Table 3. Steel properties of symbols based on the direct tension test achieved in the (NCCLR).

| Standards Specifications | Symbols No. | Min. Yielding Strength (FY), MPa | Min. Ultimate Tensile strength (FT), MPa | Total Elongation, % |
|--------------------------|-------------|----------------------------------|-----------------------------------------|--------------------|
| NCCLR Tested according to ASTMA36/ A36-2005[10] | 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[11] |             | 250≥                             | 400≥                                    | 20 ≥               |
| Japan of JIS G 3101[7]   |             | 245≥                             | 400≥                                    | 17 ≥               |
| Tested of results        |             | Conforming                       | Conforming                              | Conforming         |

Figure 4. Stress strain curve of steel plate

Figure 5. Stress-strain curve of grade 270 low relaxation seven wire strands at (12.7 mm)
4.3.3. Prestressing Steel Strands.

4.3.3.1 Prestressing Steel Strands tests.
Grade 270 low relaxations seven-wire strands of 12.7mm nominal diameter were used as prestressing strands in this study. These strands were tested in at the National Centre for Constriction Laboratories and Research (NCCLR) and conformed to ASTM A416/ A416M-12a [12]. The properties of the strands are shown in Fig. 5.

4.3.3.2 Jacking stress application.
Seven-wire strands of 12.7mm nominal diameter of grade 270 low relaxations were selected and arranged at eccentricity locations varying from 0 to 165 mm along the longitudinal axis of the steel beams. The prestressing strands were fixed initially at the dead end using grips and then individually pulled outs from the jacking end using a single prestressing strand jack operated by a motor-driven hydraulic pump. The two strands were tensioned from one end as jacking stress was gradually increased until it reached to the required jacking stress to balance the prestressing stresses and prevent biaxial bending stress that can be which introduced in the steel section during applied jacking stress ($f_{pj}$). The prestressing level was applied at 275bars, (which converts to 1,120.06 MPa). The hydraulic machine used is shown in Fig. 6.

4.4 Strain measurements in steel section.
The experimental shear strains for the tested beams were monitored through a one-channel TML data logger and switching box during application to failure. The strain gauge was fixed at distance of 248 mm (which represented the effective depth with an inclined line of 45° on the neutral axis from the support. The location of the strain gauge is shown in Fig. 7.
4.5 Load Measurements and Testing Procedure.
The steel beams tests were done in the Laboratory of the Civil Engineering Department, of the College of Engineering, Mustansiriyah University. An MFL universal hydraulic machine of 3000kN capacity was used. The steel beams were tested under one-point loads at the mid span, with a clear span of 2,850 mm. The strain gauge reading is taken at each increment. A measurement was recorded until the failure of steel beams at which time the applied load was dropped with increasing deformation, the test machine and instrumentation details are show in Fig.8.

![Test machine and loading arrangements](image)

**Figure.8 Test machine and loading arrangements**

5. Experimental parametric studies.
Seven simply supported steel beams were tested to show the shear behaviour of strengthening by external prestressing strands. All the steel beams had the same steel section, and clear span length of 2,850 mm, and strengthening was done by means of two external prestressing strands of 12.7mm diameter. The tested beams were divided into two categories according to the presence of external prestressing strands, with the first category having only one steel beam as a reference, with the second group consisting of the six steel beams strengthened by external prestressing strands, which were further divided according to the eccentricity location of the prestressing strands (e), which ranged from 0 to 165 mm at jacking stress $f_{pj}= 1120.061$ MPa. This experimental study was carried out to investigate the effect of eccentricity location on the shear behaviours of steel beams strengthened by external prestressing strands under one-point loads. The full experimental results are thud illustrated in Table 4.

| Groups | Beams No. | Series Symbols | Maximum applied load (Pu),(kN) | Maximum Exp. shear strain x10^6 | Maximum applied. shear load, (Vu),(kN) |
|--------|-----------|----------------|--------------------------------|---------------------------------|-----------------------------------|
| 1      | Ref. O    | 287.5          | 394                            | 143.75                          |                                   |
| 2      | 1 OM000   | 289            | 432                            | 144.5                           |                                   |
| 3      | 2 OM101   | 372.5          | 408                            | 186.25                          |                                   |
| 4      | 3 OM112   | 397.5          | 426                            | 198.75                          |                                   |
| 5      | 4 OM123   | 357.5          | 542                            | 178.75                          |                                   |
| 6      | 5 OM234   | 537.5          | 447                            | 268.75                          |                                   |
| 7      | 6 OM234   | 465            | 640                            | 232.5                           |                                   |
5.1 Shear load strain response.
During the test, the shear load strain curves for tested beams were slightly stiffer than for the reference beams and the percentage of stiffening increased with increases in distance of the eccentricity locations from the shear points, as shown in Fig.9.

![Figure 9](image-url) Effect of eccentricity location of prestressing strand on the shear stress strain curves of tested beams

5.2. Applied shear load of the tested beams.
During testing, it was found that the maximum shear load increased by 0.521%, 29.565%, 38.26%, 61.739%, 24.347% and 86.956% with increase the eccentricity location from 0 to 165 mm, at jacking stress $f_{pj}$ =1120.061 MPa as compared with the reference beam, as listed in Table .5. The increase in maximum shear load of tested beams is shown in Fig.10 and Fig .11. It also clear that the maximum shear load increases with increases in the eccentricity locations distances from the shear point at constant jacking stress ($f_{pj}$).

Table.5 Maximum shear load for tested beams.

| Beams No. | Series Symbols | Jacking Stress, ($f_{pj}$) (MPa) | Maximum shear load, ($V_u$),(kN) | Percentage increasing in maximum shear load ($V_u$), (kN) |
|-----------|----------------|----------------------------------|----------------------------------|--------------------------------------------------------|
| Ref. O    |                | -------                          | 143.75                           | 0                                                      |
| 1         | OM000          | 1120.061                         | 144.5                            | 0.521                                                  |
| 2         | OM101          | 1120.061                         | 186.25                           | 29.565                                                 |
| 3         | OM112          | 1120.061                         | 198.75                           | 38.260                                                 |
| 4         | OM123          | 1120.061                         | 178.75                           | 24.347                                                 |
| 5         | OM234          | 1120.061                         | 268.75                           | 86.956                                                 |
| 6         | OM105          | 1120.061                         | 232.5                            | 61.739                                                 |
5.3. Shear strain of the tested beams.
During testing, it was found that the maximum shear strain increased by 9.664%, 3.553%, 8.121%, 62.436%, 37.563% and 13.451% with increases in eccentricity location distance from 0 to 165 mm as compare with the reference beam, as listed in Table.6. The percentage increase of maximum shear strain of tested beams is shown in Fig.12.

Table 6 Percentage increasing in maximum experimental shear strain of tested beams

| Beams No. | Series Symbols | Jacking Stress, \((f_p)\) (MPa) | Maximum exp. Shear Strain x \(10^{-6}\) | Percentage increasing in maximum exp. Shear strain, % |
|-----------|---------------|-------------------------------|----------------------------------|-----------------------------------------------|
| Ref.      | O             | ------                        | 394                              | 0                                             |
| 1         | OM000         | 1120.061                      | 432                              | 9.644                                          |
| 2         | OM101         | 1120.061                      | 408                              | 3.553                                          |
| 3         | OM112         | 1120.061                      | 426                              | 8.121                                          |
| 4         | OM123         | 1120.061                      | 542                              | 37.563                                         |
| 5         | OM234         | 1120.061                      | 447                              | 13.451                                         |
| 6         | OM105         | 1120.061                      | 640                              | 62.436                                         |

Figure 10 Maximum shear loads of tested beams at different values of eccentricity

Figure 11 Percentages increasing in maximum shear load of tested beams at different values of eccentricity stress as compare with a reference

Figure 12 Maximum experimental shear strain of tested beams at different values of eccentricity
5.4 Failure Mode of the Tested beams.
In generally that the mode of failure of all tested beams under load occurred due to either flexural or local buckling, and the shear region zone was not distressed due to the applied load as the web has sufficient thickness. No holes were found in the webs despite the length of the beams; therefore, the webs of steel beams can be deemed to be capable of resisting rather large shearing forces, as shown in Fig. (13).

6. Conclusions.
Based on the results of this experimental investigation into the shear behaviour of steel beams strengthened by prestressing strands, the following conclusions are drawn.

1. The shear load strain curves for tested beams were slightly stiffer than those of the reference beams and the percentage of stiffing increase with increases in distance of the eccentricity locations from the shear points at constant jacking stress ($f_{pj}$).
2. The maximum shear load increased by 0.521%, 29.565%, 38.26%, 61.739%, 24.347% and 86.956% with an increase the eccentricity location from 0 to 165 mm from the shear points as compared with the reference beam.
3. The maximum shear strain increased by 9.664%, 3.553%, 8.121%, 62.436%, 37.563% and 13.451% with an increases in the distance of the eccentricity location from 0 to 165 mm from the shear points as compared with the reference beam.
4. The maximum shear capacity of the strengthened, tested beams increased with increases in strand eccentricity at constant applied jacking stress. The enhancement in ultimate moment
capacity of strengthened, tested beams was 86.956% in the OM234 sample compared with the reference beam.

5. The straight strand profile as defined by OM234 samples had the least shear strain for strengthened tested beams as compared with the reference beam.

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