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**Original Research**

# EFFECT OF THE STRANDS FIXITY PROFILE SHAPE ON THE FLEXURAL BEHAVIOR OF STEEL BEAMS

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**Abstract:** This study concerns the effect of the external prestressing strand shape profile on the flexural behavior of steel beams. Seven steel beams that have the same cross-section are strengthened by external strands fixed by using Saddle Points of Deviation (Deviators). Based on two criteria, beams tested are divided into two categories whether external prestressing with fixity strands is present. The first group includes only one beam as a reference, while the second group deals with beams strengthened by two external strands. Six samples have been separated according to the eccentricity for external prestressing at a jacking stress of 815 MPa. During testing, it was discovered that the moment-curvature responses at the bottom and top flange region were stiffer than those in the reference, and the degree of hardening increases with eccentricity increasing. However, failure occurs with a slight warning as a result of insufficient ductility. Due to the presence of external prestressing, the ultimate moment capacity is enhanced by approximately 6.1%, 31.7%, 38.5%, 57.6%, 29.4%, and 80.2% as compared to the reference. Finally, the radius of curvature at the top flange region for strengthening samples has grown by approximately -16.7%, 8.0%, -26.9%, 21.5%, 17.5%, and 17.4% as compared to the reference case. In contrast, the percentage of the radius of curvature at the bottom flange region for strengthened samples dropped to 24,9%, 73.9%, 83.2%, 83.6%, 69.2%, and 89.0%, respectively, with an increase in the eccentricity position as compared to the reference.

**Keywords:** *External prestressing; Fixity of prestressing strands; Flexural behavior; Strengthening*

## 1. Introduction

As a result of its uniformity, high strength, toughness, performance, and homogeneous properties, steel is by far the most popular and efficient material for construction, with strength nearly ten times greater than that of concrete [1]. Its most important characteristics include excellent tensile strength, durability, and formability. Prestressing is the process of applying uniform pressure to a structural member to improve its ability to withstand service loads. A marvelous technique that increases the performance and durability of structural components by creating internal stresses in those parts of the element that are subject to external loads [2, 3].

## 2. External Prestressing

A form of post-tension technique known as external prestressing involves attaching strands to the exterior of a structural member and applying external prestressing stresses to them through end anchorage. It is a brilliant and effective approach for repairing and strengthening structural components, and it is

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typically applied to increase a building or bridge's resilience to overloading and fatigue [4]. Using steel anchorage plates at the ends makes it possible to use external prestressing strands with steel beams. According to the loading conditions, there are multiple ways to fix the strands along the beam profile. Fig. 1 shows three design profiles that are used, straight, draped, and parabolic which prevent slippage in the external strand, depending on bending moment diagrams [5]. Once the strands are fixed, an identical jacking force is applied at the ends to induce stress on the strands which is transferred to the beam via the end fixture as a prestress. Care must be taken during this process to ensure stability and avoid unnecessary distortions and biaxial bending in the members [6, 7].

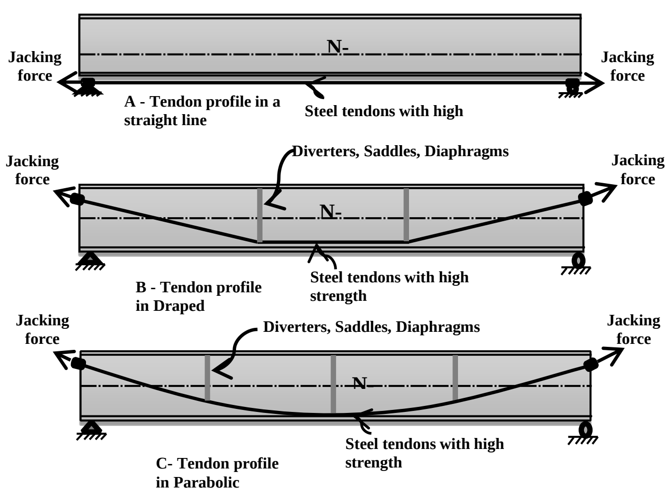



**Figure 1.** Strengthening methods.

## 3. Significance of the Field Study

The purpose of this research was to investigate and gain a better knowledge of how the external prestressing strand's fixity and profile influence the flexural behavior of steel beams.

## 4. Experimental Work

### 4.1. Descriptions of Samples

The main variables in this study are the external prestressing with fixity strands and the organization of the prestressing strands at different positions (i.e., the eccentricities location of prestressing strands). Six steel beams with simple supports were retrofitted with fixity strands under a single-point load. The beams tested are divided into two groups depending on the existence of external prestressing with fixity strands. The first category includes one beam as a reference. By testing this beam as a benchmark, any changes in behavior due to prestressing are quantified and compared. This beam is not subject to any prestress and represents the majority of arrangements observed in structures. The second group deals with beams retrofitted by two external prestressing with fixity strands. It includes six samples that have been separated depending on the external prestressing eccentricity which has a jacking stress ($f_{pj}$) of 815 MPa. All beams are I-beams with identical sections and steel plate ends which are 25x125x250 mm in size. The overall length of each beam is 3050 mm, and wire rope clips are used to secure the external prestressing strands.

### 4.2. Schemes for Specimens Identification and Strengthening

The following series system is used to categorize the tested beams, depending on how the external prestressing fixity strands are laid out:

$SiX_1X_2$

Where: -

R: Steel beams reference

Si: strand shape profile denoted by: -

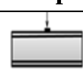
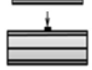
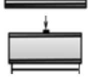
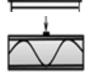
1- Straight strand, 2 - Draped strand, and 3- for sine wave strand by initial jacking stress ($f_{pj}$ = 815 MPa)

$X_1$: Mid-span eccentricity of the external strand, denoted from 0 to 2.

$X_2$: End-span eccentricity of the external strand, denoted from 0 to 3.

All descriptions of the tested beams can be arranged using the flowchart shown in Fig. 2 and Table 1.

**Table 1.** Tested beams specifications

| Sample | Profile | Shape | $e_1$* | $e_2$ ** |
|---|---|---|---|---|
| R | --- |  | --- | --- |
| S100 | Straight (00) |  | 0 | 0 |
| S210 | Draped (10) |  | 96 | 0 |
| S211 | Draped (11) |  | 96 | 20 |
| S112 | Straight (12) |  | 96 | 96 |
| S123 | Straight (23) |  | 165 | 165 |
| S310 | Sinewave (10) |  | 96 | 0 |

*Mid-span eccentricity, **End-span eccentricity

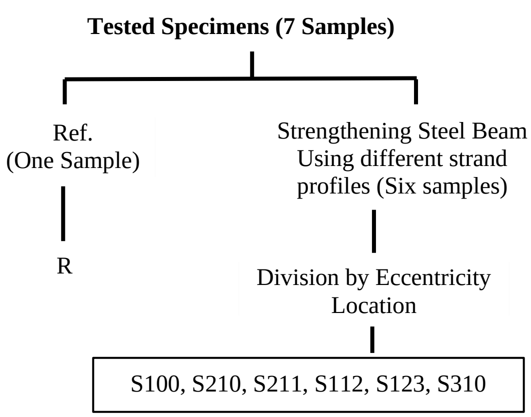



**Figure 2.** A flowchart showing the experimental designation for the tested beams

### 4.3. Sections

I-steel section (H = 248 mm, B = 124 mm) with a thickness of 5mm for the web and 8mm for the flange was employed in this work. A type of hot-rolled steel called SS400 is frequently utilized in applications for basic structural parts. Which has a yielding strength of 360 MPa ultimate tensile strength of 510 MPa and elongation of 20%, all of these mechanical characteristics satisfied the SS400 specification [7, 8]. End steel plates were joined together using H248x124 and E7018 electrodes for 5mm fillet welds, enabling the strands to pass through and allowing them to be secured [9]. To minimize the stress concentration near the end plate hole, the exterior prestressing strands must be as perpendicular to the end plates as practicable [10, 11].

### 4.4. Prestressing Technique

*4.4.1. Test of Prestressing Steel Strands*

In this study, seven-wire steel strands, low relaxation, of Grade (270), and a diameter of 12.7 mm were adopted. The strands were examined and tested to meet steel and ASTM specifications [12 - 14].

*4.4.2. Application of jacking stress*

The 12.7 mm diameter strands were positioned according to the required profiles by passing them via the steel beams' longitudinal axis. The strands are initially anchored at the dead-end using holds, they are then pulled out one at a time from the jacking end using a single prestressing strand jack that is powered by a hydraulic motor. All strands were tensioned simultaneously from one end while gradually raising the jacking stress till achieving the designated pressure to equilibrium the strand loads and prevent the introduction of biaxial bending into the section. Fig. 3 depicts the hydraulic device that is employed.

**Figure 3.** The prestressing hydraulic machine

*4.4.3. Fixity of external prestressing strands by using Saddle Points of Deviation (Deviators).*

Saddle points or deviators for steel structures are any segments made from steel plates or small steel sections, connected with the structural members either by bolting or welding, to provide the appropriate profile of the external prestressing strand according to the loading applied and bending moment diagrams. In this study, double angle (2L25x25x4 mm) sections were used as deviators welded on the web of the steel beam at distances 250 mm from center to center. The double angles were drilled by a perforation machine, the holes were drilled slightly wider than the diameter of the strand, and then wire rope clips, sometimes called U-bolt clips, were used to clamp the strands. Wire rope clips fitting consist of a U-bolt with a 16 mm diameter and has a saddle secured by two nuts of size 19 mm, these are welded on the 2L25x25x4 mm, then the external strand is passed through the holes in the end anchorage steel and deviators. At the same time, stress is applied to both strands from one end. To prevent biaxial bending of the specimens, adjusting the prestressing force in the strands was done with great care. Next, the U-bolt is applied fixed and fastened so that the U-section is in contact with the strands. Typically, the saddle is provided with a right-hand helix. Finally, a torque wrench was used to apply a specific torque to tighten the nuts. It's crucial to make sure that wire rope clips are installed correctly to create the required strand profile.

### 4.5. Testing Procedure

The tests were conducted in the laboratories of the Civil Engineering Department at the College of Engineering, Al-Mustansiriyah University. A universal hydraulic machine with a 3000 kN capacity was used, which applies a single load at the midpoint of a 2850 mm simply supported beam. At each increment, readings from the strain gauges are recorded. The test device and equipment details are shown in Fig. 4.

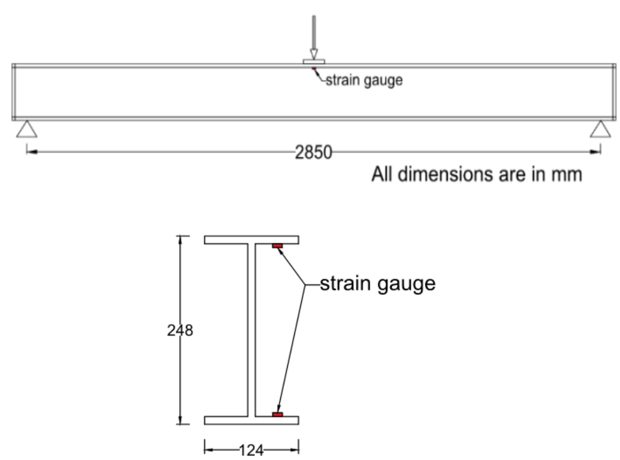



**Figure 4.** Test device, strain gauges, and applied load locations

Two strain gauges are installed at the midpoint along the length of the beam and a quarter length from the edge across the width of the top and bottom flanges, as shown in Fig. 5. Measurements are taken up to the point of failure which is defined by increasing deformation and a drop in load.

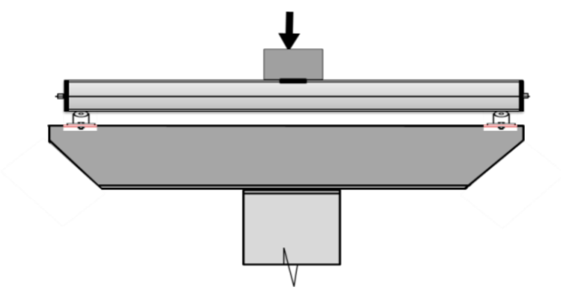


**Figure 5.** Location of the strain gauges

## 5. Results and Discussion

The purpose of this experimental study is to explain how the eccentricity position and fixity of this type of prestressing (external) affect the flexural behaviors of beams under a single-point load. To keep an eye on the experimental results, two channels were set up in the middle of the tested beams when the load was applied until failure. A strain gauge was set at the top and bottom of each flange to measure the strains over a distance of one-fourth the width of the flange. Table 2 displays the experimental results for the beams that were investigated.

**Table 2.** Experimental results for the tested beams

| Sample | Moment (Mu), (kN.m) | Top flange curvature* | Bot. flange curvature* |
|---|---|---|---|
| R | 204.84 | 107.92 | 134.75 |
| S100 | 217.31 | 89.90 | 101.22 |
| S210 | 269.68 | 119.01 | 34.47 |
| S211 | 283.58 | 80.61 | 22.15 |
| S112 | 265.05 | 129.25 | 40.63 |
| S123 | 369.08 | 131.16 | 14.28 |
| S310 | 322.76 | 133.96 | 21.60 |

** Max. curvature at mid-span locations ($10^{-6}$/mm)*

### 5.1. Moment curvature response.

The response of moment-curvature for the strengthened beams with external prestressing with fixity strands at the bottom and top flange region was found to be stiffer than the corresponding values for the reference beam. Also, as the eccentricity locations increased, the percentage of hardening increased, this is a result of the axial force generated by the jacking stress ($f_{pj}$) in the external strands, which led to the development resistance in the web and bottom flange. This is a result of the prestressing; the presence of the external strand provides extra resistance against the applied loading. On the other hand, the failure occurs suddenly as a result of inadequate ductility due to resistance and stiffness induced by the existence of external strands with fixity [15 - 17], as shown in Figs. 6 and 7.

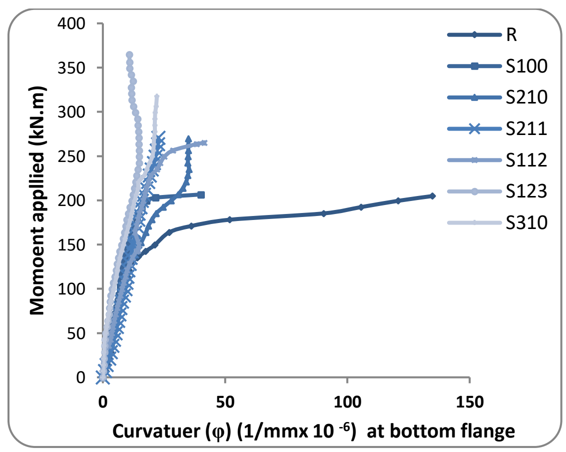



**Figure 6.** Moment-curvature curves according to the bottom flange strain

### 5.2. Moment carrying capacity.

The testing showed that, when compared to the reference beam, the prestressing increased the moment carrying capacity by approximately 6.09%, 31.65%, 38.44%, 29.39%, 57.57%, and 80.17% as the location of eccentricity is increased until 165 mm. This is because the initial moment is provided by the prestressing force, which is the moment generated by the applied external load as demonstrated in Table 3 [15 - 17].

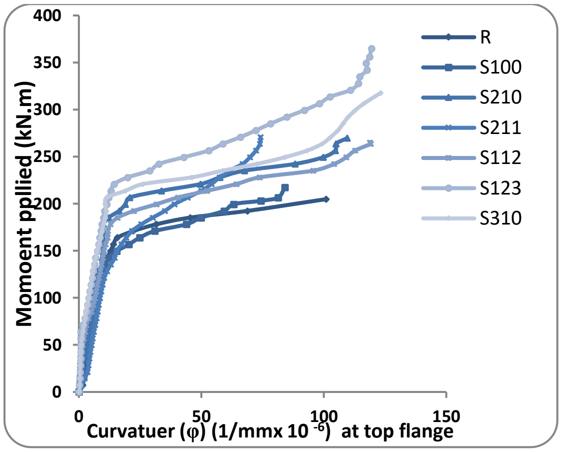



**Figure 7.** Moment-curvature curves according to the top flange strain

Figs 8 and 9 depict the growth in the moment carrying capacity of the prestressed beams. The test results indicate that the moment carrying capacity increases with increasing eccentricity locations. Additionally, the presence of an external strand enhanced the resistance of the web and bottom flange and increased the beams' ability to resist the applied load.

**Table 3.** Moment results of the tested beams

| Sample | Moment (Mu), (kN.m) | Moment increasing (%) |
|---|---|---|
| R | 204.84 | 0.00 |
| S100 | 217.31 | 6.09 |
| S210 | 269.68 | 31.65 |
| S211 | 283.58 | 38.44 |
| S112 | 265.05 | 29.39 |
| S123 | 369.08 | 80.17 |
| S310 | 322.76 | 57.57 |

### 5.3. Curvature of the top flange

During the tests, it was observed that the radius of curvature of the top flange, in comparison to the reference beam, had changed in the magnitude of -16.70%, 10.28%, -25.31%, 19.76%, 24.12%, and 21.53% with an eccentricity increasing to 165 mm (Table 4).

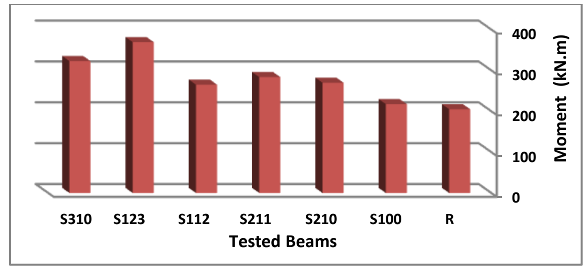



**Figure 8.** Moment results of tested beams

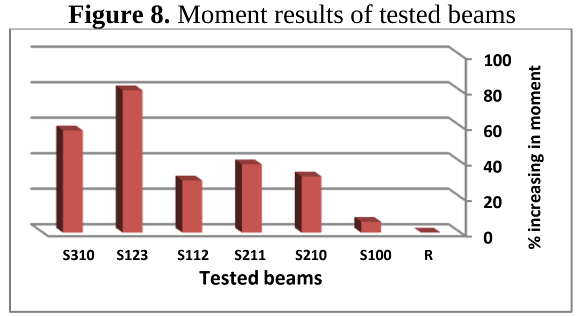



**Figure 9**. Moment increasing of tested beams

As a result, it is evident that as the eccentricity increases, the radius of curvatures at the top flange increases. The negative sign in the percentage increase indicates how local buckling in the top region caused the radius of curvatures at the top flange to decrease.

**Table 4.** Maximum top flange curvature of the tested beams

| Sample | *Maximum Curvature ($10^{-6}$/mm)* | *Increase in curvature, (%)* |
|---|---|---|
| R | 107.92 | 0.00 |
| S100 | 89.90 | -16.70 |
| S210 | 119.01 | 10.28 |
| S211 | 80.61 | -25.31 |
| S112 | 129.25 | 19.76 |
| S123 | 131.16 | 21.53 |
| S310 | 133.96 | 24.12 |

However, the failure manifests as a small warring due to the tested beams' poor ductility as a result of the presence of external prestresses with fixity strands [18 -20].

### 5.4. Curvature of the bottom flange

During the testes, it was also observed that with an increase in eccentricity position from 0 to 165 mm at $f_{pj}$ of 815 MPa, the maximum bottom flange's curvature of the tested beams decreased. As a result, it can be seen that the maximum bottom flange's curvature decreased with fixity external prestressing strands were reduced to 24.89%, 74.42%, 83.57%, 69.40%, 83.97% and 89.40% in comparison with the reference beam, as shown in Table 5. It can also be seen with increasing eccentricity positions at mid-span with constant jacking stress, which was caused by the presence of an external prestressing strand, improving each of the bottom flange and web resistance and helping the sample to resist the applied load.

**Table 5.** Maximum bottom flange's curvature of the tested beams

| Sample | ***Maximum Curvature ($10^{-6}$/mm)*** | ***Decrease in curvature, (%)*** |
|---|---|---|
| R | 134.75 | 0.00 |
| S100 | 101.22 | -24.89 |
| S210 | 34.47 | -74.42 |
| S211 | 22.15 | -83.57 |
| S112 | 40.63 | -69.85 |
| S123 | 14.28 | -89.40 |
| S310 | 21.60 | -83.97 |

## 6. Conclusions

In comparison to the reference beam, the moment-curvature responses for external prestressing steel beams with fixity strands at the bottom and top flange regions are stiffer, and as the eccentricity locations are increased, the percentage of hardening increases. Due to poor ductility in the beams from having exterior prestressed fixity strands, the failure manifests as a minor warning. The behavior of moment curvature for the prestressed beams is stiffer and less ductile than the corresponding behavior of the reference beam. The moment carrying capacity is improved by 6.09%, 31.65%, 38.44%, 29.39%, 80.17%, and 57.57% as the increasing eccentricity position from 0 to 165 mm, related to the reference beam. The increasing percentage in the radius of curvature at the top flange of the prestressed samples increased to -16.70%, 10.28%, -25.31%, 19.76%, 24.12%, and 21.53%, respectively, in comparison to the reference beam. The increasing percentage in the radius of curvature at the bottom flange region for steel beams retrofitted by external prestressing with fixity strands reduced to 24.89%, 74.42%, 83.57%, 83.57%, 89.85%, and 69.85%, respectively, in comparison to the reference beam.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## Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

## Author Contribution Statement

The authors proposed the research problem, developed the model of the research, and computed the results. They also discussed the findings and contributed to the final manuscript.

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