EXPERIMENTAL EVALUATION OF THE STRUCTURAL PERFORMANCE OF DEFORMED WIDE-FLANGED BEAM RETROFITTED WITH HARPED EXTERIOR POST TENSIONING SYSTEM

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Abstract: An innovative Exterior Post Tensioning (EPT) system is proposed which enables a structural beam to be retrofitted by simply using a turnbuckle to induce the prestressing force. The use of turnbuckle instead of the usual hydraulic jack would greatly reduce the cost of retrofitting. The proposed system utilizes two deviators to produce a harped prestresing tendon. The study aims to evaluate the performance of harped EPT in retrofitting a deflected wide-flanged steel beam. The experiment involved applying one point load to the wide flange steel beam to produce deflection beyond its service limit or up to the inelastic stage. Then, the harped EPT was applied to counteract the deflection of the beam. Afterwards, the beam is loaded again to determine the improvement in strength and serviceability. Loads, deflections, and strains were carefully monitored throughout the experimental test. Moreover, the experimental setup was designed to investigate the effect of two different deviator ratios. The deviator is a protrusion attached to the beam to control the direction of the tendon. The beams that were tested with the harped EPT were compared to the unharped EPT system in terms of the load carrying capacity, consistency, and serviceability. Results showed that both deviator ratios demonstrate a similar reduction in deflection and similar effectiveness in carrying loads. However, the setup with the deviators located nearer the supports showed a better serviceability in terms of energy dissipation. The proposed system is proven to be an effective method of retrofitting because it was able to repair a deformed beam that had gone beyond its yield strength. Compared to previous study, the strength and stiffness of the harped EPT increased. Lastly, early failure at the connection was prevented.

Key Words: Exterior post tensioning, retrofitting, strengthening, prestressing,

1. INTRODUCTION

Nowadays, civil engineers are faced with problems of aging structures including steel structures. Deterioration of materials, excessive service loads, and other environmental factors have caused some structural members, usually the beams, to exhibit unsightly deflections and doubt in their strength and serviceability. Several studies on retrofitting of structural steel beams are being undertaken. One of the retrofitting techniques uses an Exterior Post-Tensioning (EPT) system. This usually utilizes a hydraulic jack to apply prestressing force to a beam to improve its load carrying capacity and to counteract deflections.

In retrofitting a beam the 3 things should be considered: the system should be light weight, easy to assemble and is readily available in the country. This is envisioned to be accomplished by using an innovative Exterior Post Tensioning (EPT) system which enables a structural beam to be retrofitted by simply using a turnbuckle to induce the prestressing force.

This study aims to evaluate the performance of harped exterior post-tensioning in retrofitting a deflected wide-flanged structural steel beam. Specifically, the study aims to:

a) Study the flexural behavior of wide-flanged steel beams retrofitted with harped EPT,
b) Analyze the effects of varying the deviator ratio to determine the most effective one
c) Determine the effectiveness of the harped EPT system by establishing its consistency, serviceability and other manifestation
d) Compare the flexural strength of harped and unharped EPT system

2. PREVIOUS STUDY

The research of Adiaz, et al (2010) in their thesis *Effects of Exterior Post-Tensioning on Retrofitting Steel Wide Flange Beams* has proven that EPT is applicable in repairing and increasing the load capacity of steel beams. However, such design was found out to have weakness at the anchorage connection and therefore not being able to maximize its full potentials. Although the EPT was still functional up to 45% increase in the original load carrying capacity of the beam, the weld along anchorage to the beam failed. Due to such failure in the connections, the harped EPT is used in this study as an alternative option.

This current study aims to repair a wide-flanged steel beam that has reached its yield strength using a harped exterior post-tensioning method without compromising the capacity of the anchorage. Deviators were introduced in the proposed model to position the steel cables at a certain angle to prevent unwanted failure in the connections. As a result, the moment capacity of the beam further increased.

3. METHODOLOGY

The study primarily focused on attaining a better model of EPT considering only materials readily available in the country and can easily be installed. The design consists of a beam, with a length of 1.50 meters and bolted anchorages located near the ends of the beam.

3.1 Test Specimens

The parameters of the experimental program were three (3) inelastic displacements (1.5δy, 2δy and 2.5δy) applied to the beam and two (2) deviator ratios. This resulted to 6 cases and two specimens were tested for each case. Hence, a total of twelve (12) steel beam specimens were prepared and tested. The built-up wide flange beam consisted of three steel plates welded to form a built-up section having a flange width of 100mm, web depth of 50mm, and flange and web thickness of 6mm. The EPT system consisted of steel cables anchored on one end and connected in between the deviators with a turnbuckle. Two deviators were mechanically welded and were located in between the anchorages. A pulley was located at the end of each deviator to minimize friction produced by the tightening of the steel cable. A typical beam specimen with harped EPT is shown in Figure 1. In this study, two deviator ratios were examined.

3.2 Deviator Ratio

The deviators used in the EPT system were varied into two different deviators ratios, that is, the ratio of the distance between the deviators with respect to the supported length of the beam. The two ratios chosen were ¼ L and ¾ L, where L is the length of the beam. The two ratios were investigated in order to analyze which would provide the more effective and efficient design for retrofitting damaged beams. A sketch of the two deviator ratios is shown in Figure 2 below.

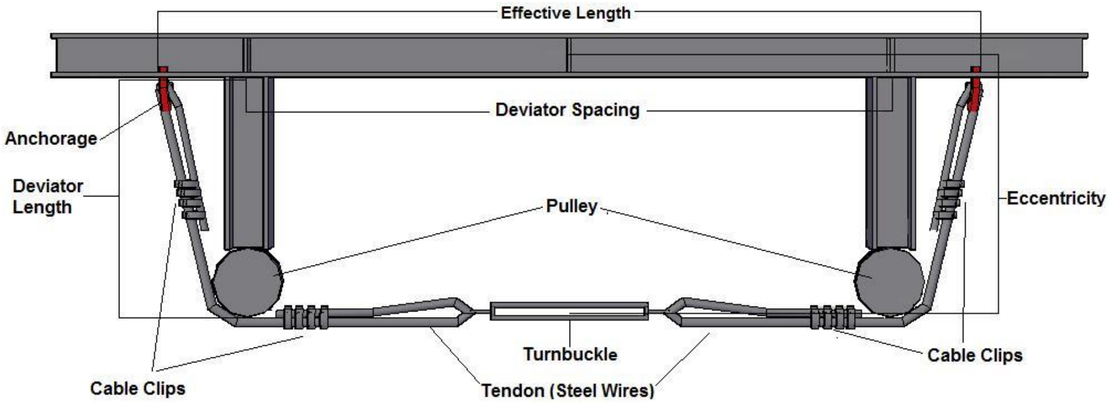

Figure 1. Details of Harped EPT System

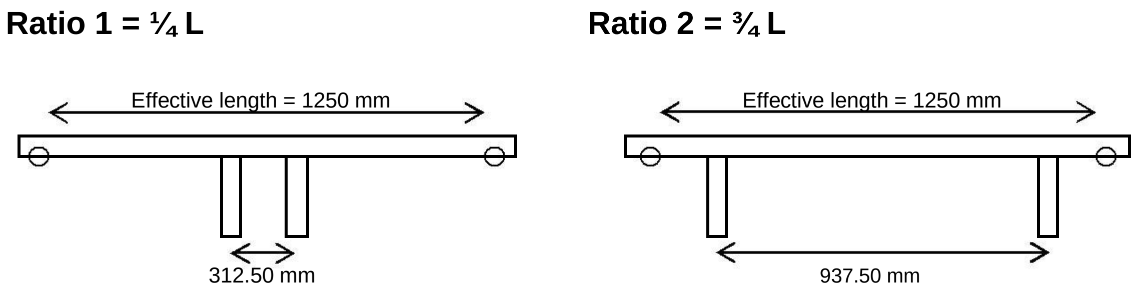

Figure 2. Different Deviator Ratios with corresponding Length

3.3 Test Conditions and Loading Cycles

Initially, two beam specimens were tested under the elastic range without applying EPT to verify the elastic behaviour and yielding of the beam. Then the beams were tested under three different displacement conditions and two deviator ratios. The displacement conditions were obtained by applying load that will produce the following mid span displacement: 1.5δy, 2δy and 2.5δy where δy is the mid span deflection at yield. For each test condition, three loading cycles were performed. The purpose of the test cycles is to investigate the effect of adding EPT to the deflection and load capacity of the damaged beam. The 1st cycle is loading the beam to the specified inelastic deflection and then applying the EPT to counteract the displacement. The 2nd cycle is reloading the beam until it reached the same load capacity of the 1st cycle, afterwards EPT is again applied. The third cycle is testing until final failure occurred.

3.4 Experiment Testing Setup

The beam specimen was tested in a beam test rig. A concentrated load was applied at mid span with the use of a hydraulic jack and the load cell recorded the loading activity. Two displacement transducers were placed at the mid span to record the deflection of the beam. Two pi gauges were also placed at the top of the beam, aligned to each deviator. For the bottom portion of the beam, two pi gauges were placed at the midspan to measure the strains. Sketch of this setup and a picture of the actual testing are shown in Figure 3. For the application of EPT, the tendons were placed on each side of the anchorages, and then it passed through the pulley located under the deviator. The tendon was connected to a turnbuckle that can apply tensile force when turned. Strain gages were attached to the tendon so that that the applied tensile force can be monitored.

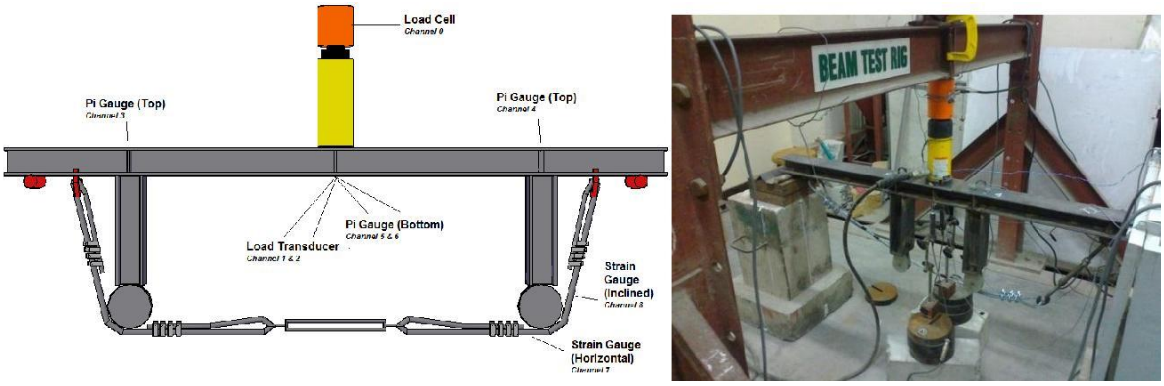

Figure 3. Sketch of Test Setup (left) and Photo of Actual test setup (right)

4. ANALYSIS OF TEST RESULTS

Presented here are concise summary of test results and analysis. Readers are urged to refer to the theses of Astillero et al (2012) and Adiaz et al (2010) for details. With a yield strength of 345 MPa, the theoretical displacement of the beam at yield point is δy=9.09 mm and the corresponding theoretical load is 32.03 kN. To verify these values, a pilot test was done. The beam was loaded beyond the theoretical elastic range and the load-displacement diagram was plotted as shown in Figure 4. The figure indicates that the test results agreed well with the theoretical values.

The maximum load applied at each load cycles are tabulated in Table 1. In comparison to the unharped EPT system of Adiaz et al, the harped EPT system has improved its load carrying capacity. In the previous study, failure occurred at the welded connections of the anchorage at a load of 62.2 kN. For the harped EPT system, a maximum load of 93.4 kN was reached. Furthermore, the failure occurred on the tendons and not at the connection. This means that the harped EPT system was able to maximize the strength of the beam.

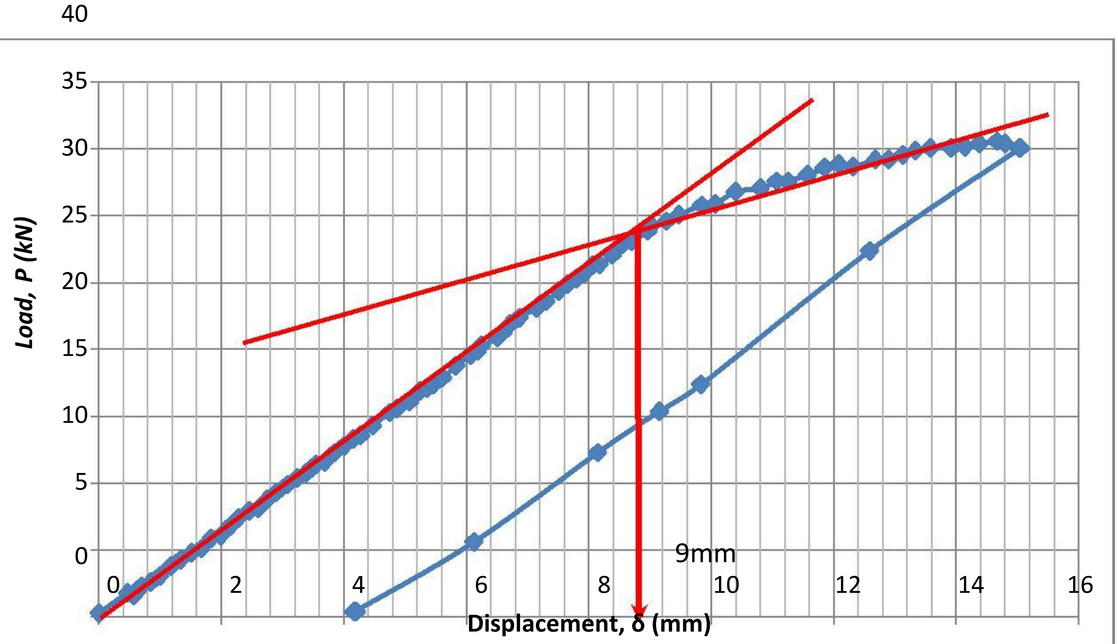

Figure 5. Load-Displacement Diagram from Pilot Test

Table 1. List of Specimens and Corresponding Maximum Load at Each Test Cycle

Ratio 1 (Max Load, kN)					Ratio 2 (Max Load, kN)				
Beam No.	Test Condition	1st Cycle	2nd Cycle	3rd Cycle	Beam No	Test Condition	1st Cycle	2nd Cycle	3rd Cycle
1		33.6	37.4	44.1	7		31.1	35.6	52.9
2		34.9	35.9	72.2	8		34.7	36.1	59.9
3		38.1	39.6	79.2	9		30.4	36.9	60.2
4		38.1	39.7	87.2	10		38.7	38.6	75.9
5		39.4	39.9	93.4	11		35.6	35.2	n/a
6		38.4	38.4	79.4	12		36.2	n/a	74.9

4.1 Analysis of Load –Displacement Diagrams

Load-displacement diagrams (see example in Figure 5), showed that as the load increases, the displacement of the beam also increases. It was generally observed that in all 1st and 2nd cycles (curves look similar for these two cycles), loading without EPT produced larger amount of displacements compared to loading with EPT having similar magnitude of load. For the load-displacement diagrams of 3rd cycle, it was observed that a higher magnitude of force for loading with EPT was needed to achieve the same amount of displacement in loading without EPT. Thus, it can be said that the application of EPT in the beam increased its strength. The harped EPT system was also able to decrease the displacement which shows that the serviceability was improved.

To further investigate if there was a significant effect in the variation of the deviator spacing of the EPT system, the increase in stiffness for specimens with EPT was also investigated. The percentage increase in stiffness for each deviator ratio was evaluated. Ratio 1 has an average percentage increase of 53.64% while Ratio 2 has a value of 48.29%. However, using statistical tools (Shapiro-Wilk test and T-test) it was found out that there is no notable effect of using either Ratio 1 or 2.

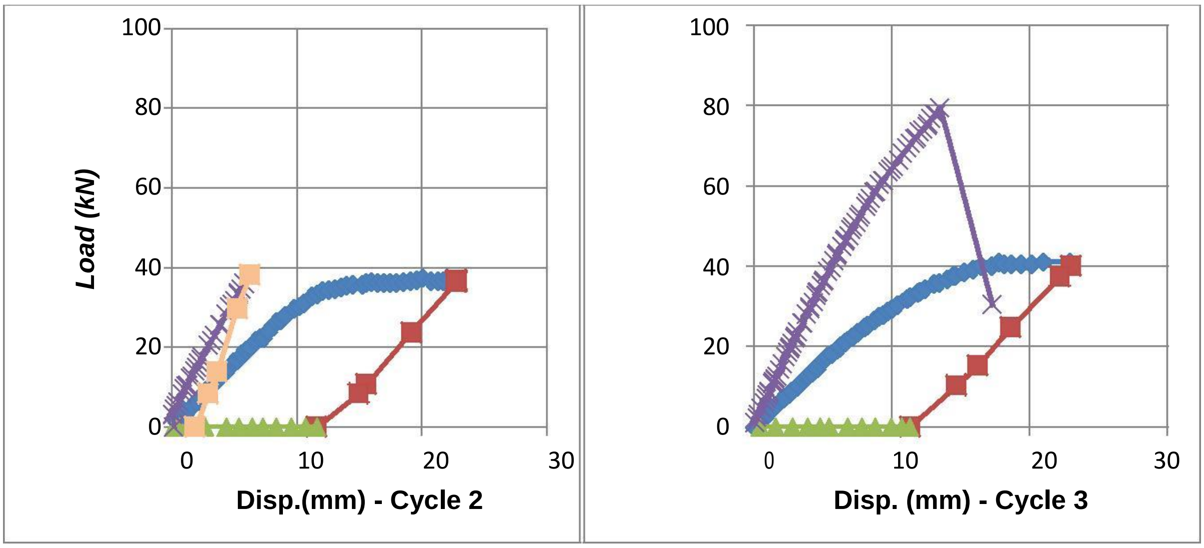

Figure 5. Typical load-displacement diagram for cyclic loading

4.2 Analysis of Moment-Curvature Diagrams

The moment-curvature diagrams were also investigated. It was observed in the diagrams that the total theoretical moment of the beam, $M_{T(theo)}$ at yield strength was 11.21 kN-m. However the experimental moment of the beam, $M_{T(expt)}$ in most cases exceeded the theoretical moment of the beam. This indicates that the actual strength of the beam was larger than the theoretical or the computed moment of the beam. The average experimental moment was 13 kN-m. It was observed that the averaged ratio of the theoretical over the experimental moments ($M_{T(theo)}/M_{T(expt)}$) was 91% for Ratio 1 while 93% for Ratio2. Based on these percentages, it may be deduced that the harped EPT system was able to utilize the strength of the beam before the EPT took effect.

4.3 Effectiveness of Harped Exterior Post-Tensioning

The energy dissipated by the beam can be calculated from the load-displacement diagrams using trapezoidal method. It was observed that the harped EPT dissipated almost the same energy per cycle of the beam which indicates good consistency. This signifies that the harped EPT can be applied over and over with no significant change in its effectiveness. Moreover, statistical analysis showed that energy dissipation was significantly affected by the deviator ratio. Ratio 1 resulted to higher energy dissipation than ratio 2. Hence, ratio 2 can be deemed better than ratio 1 as it lowers the energy dissipation of the beams.

5. CONCLUSIONS

Previous studies conducted by Adiaz, et al showed that the application of EPT can be utilized in retrofitting structural steel beams. However, it had failures primarily on the welds of the anchorages; thus, not maximizing its full use. The solution proposed is to introduce harped tendons jacked by a turnbuckle. Test results showed that the harped system was able to reach a maximum significantly higher than the unharped system. The harped EPT also prevented early failure due to welding failure at the connection.

Comparison between deviator ratio 1 and ratio 2 in terms of load-displacement and moment-curvature curves did not show notable effect based on statistical analysis. However, in terms of effectiveness is dissipating energy, ratio 1 dissipates more energy making it less efficient than ratio 2. Statistical analysis confirmed that there is a significant difference in energy dissipation between the two ratios. Furthermore, based on experimental observations on the practicality of the design, it is easier to apply prestress using ratio 2.

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