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Behaviour of Distressed RC Beams Retrofitted By External Prestressing Using Trapezoidal Tendons

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Rectangular RC beams were tested before and after retrofitting by external Prestressing. RC beams of 150 mm x 275 mm section and 4 m length were subjected to monotonically increasing static two-point load and the cracks were induced to a limit such that the strain in reinforcing steel was around 85 % of the yield strain. Retrofitting by external Prestressing using trapezoidal tendons was done while the member was subjected to superimposed dead weight of a bridge girder, equivalent to 25 % of the ultimate load of the beam. Retrofitted beams were tested by monotonically increasing two-point load. It was observed that ultimate flexural capacity of the beam is increased by 59 %. Around 10 % of loss was observed due to the friction between tendon and deviators. An analytical model is developed and compared with experimental results.

Keywords: Experiment, Modeling, RC Beams, Flexure, Strengthening, Retrofitting, External Prestressing

Introduction

External Prestressing is being used for retrofitting of distressed concrete bridges and also for new bridges of monolithic and segmental constructions. External Prestressing is a post-tensioning method, in which tendons are placed entirely outside the concrete members and the Prestressing forces are transferred to the concrete member through anchorages and deviators. Although the technique is successfully used for retrofitting of bridges, some of them have shown signs of distress in the post-retrofitting life. Therefore, it is necessary to study the post-retrofitting behaviour of concrete members retrofitted by external Prestressing by taking into account of parameters: influence of retrofitting on untensioned steel, friction at deviators, and recovery of deflection. Harajli[1], Ghallab and Beeby[2], Elrefai *et al*.[3], Sirimontree and Teerawong[4], Burningham *et al*.[5], Ghanem *et al*.[6], Lee[7], and Pisani[8] have reported the efficiency of external Prestressing in improving the load carrying capacity and performances in different cases. This paper presents the experimental results followed by analytical model on testing of two RC beams, which were distressed and retrofitted by external Prestressing.

Experimental investigations

OPC 53 grade cement of specific brand and particular manufacturing unit was used. Concrete mix ratio of 1: 1.59: 2.79 with water-cement ratio of 0.51 was used to achieve M 40 concrete. Tension test on 12 mm dia reinforcement bar was carried out as per ASTM standards: E8/E8M-09. The yield strain and the yield stress were observed as 0.0023 and 433.70 MPa respectively. Tension test on High tensile steel wire (7mm dia) was conducted as per ASTM standard: A 370, and ultimate strength was observed as 1478 MPa. Beams of section size 150 mm x 275 mm with 3.74 m span were used. Distress was induced by means of cracks. Beams were subjected to two point static loading and cracks were induced such that the maximum strain in steel obtained around 85 % of the yield strain. The corresponding strain in reinforcing steel were observed as 2030 and 1850 micro strain for specimens EPS-B7 and EPS-B9 respectively. Retrofitting was carried out by applying external Prestressing of trapezoidal profile of tendons, using 2 nos of 7mm dia high tensile steel wires, while keeping 9.5 kN actuator load (25% of the ultimate load), which simulated the super imposed dead weight of a bridge girder. Test setup and testing of retrofitted specimen EPS-B7 are shown in Figure 1 The effective pre stress of 756 MPa and 582 MPa were given to specimens EPS-B7 and EPS-B9 respectively. Deflection of specimens was recovered from 8.87 mm to 3.52 mm, and 4.3 mm to 0.61 mm for specimens EPS-B7 and EPS-B9 respectively. 60 % and 86 % of deflection were recovered due to external Prestressing for EPS-B7 and EPS-B9.

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Fig.1 — Test setup and testing of distressed RC specimen retrofitted by external Prestressing EPS-B7

Tendons were divided into three segments since two deviators were provided in the flexural zone of the specimen, and stresses in different segments were varied. It was in the order that strain in the segment-pulling end was higher than that of other two segments, which are shown in Figure 2 for specimens EPS-B7 and EPS-B9 respectively. This may be due to the friction developed at deviators, which lead to loss of pre stress around 10 %. Testing of retrofitted beams by static load were started immediately after completing the external Prestressing, till failure to examining the behavior. The beams were failed at 78 kN and 81 kN for specimens EPS-B7 and EPS-B9 respectively with concrete crushing in the extreme compressive fibre.

Modeling on retrofitted beams

Basic assumptions: i) Deviators and anchorages are functioning well; ii) Second order effects in externally pre stressed members are ignored; and iii) Friction at deviators (both slip and non-slip conditions) are ignored.

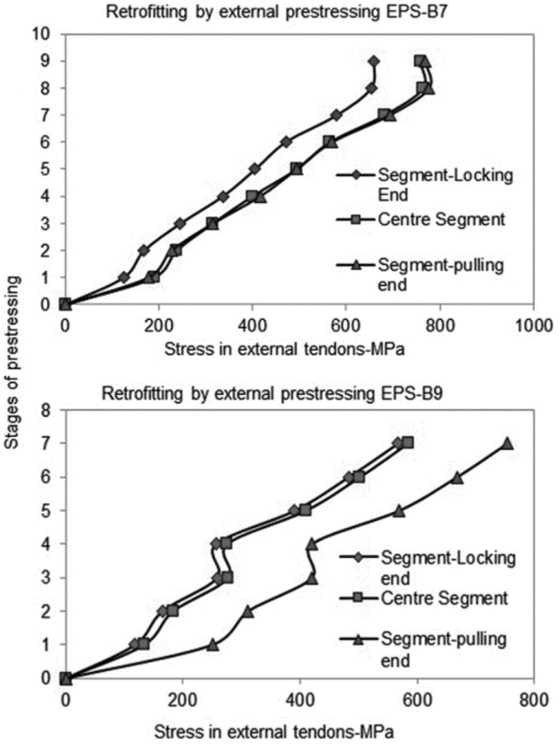


Fig. 2 — Stress variations in tendons at different segments for EPS-B7 and EPS-B9

Stresses at various state of behaviour

As the analysis of concrete members pre stressed by external tendons is member dependant, section analysis using strain compatibility is not possible. Therefore, compatibility between deflection at one of the deviators' location and strain increase in external tendons beyond effective pre stress was applied. Analysis of externally pre stressed cracked RC beams was carried out using force concept method. At the stage of effective pre stress, tensile force offered by Tendon T and the Compressive force offered by the resultant compression C are in same position. When the moment due to self weight and live load acting upon the member M_p the resultant compression shift from the position of tensile force, which is equal to $\frac{M_p}{T}$. Moreover, eccentricity will go on vary, depending upon the shift in position of resultant compression. Shift in the position of resultant compression = C_{shft}. There was no shift in resultant compression line, when $C_{shft} = 0$ and $C = T$. When the position of the resultant compression lies above the tendon line and below the original eccentricity, $0 \leq C_{shft} \leq e$. The distance of the location of resultant compression from the centre line of the member$\left(\frac{h}{2}\right)$, i.e., e_{new} was computed as $e_{new} = e - C_{shft}$. Accordingly, stresses in concrete member at top and bottom fiber due to external Prestressing S_{top} were computed as follow:

$$S_{top} = \frac{P}{A} - \frac{P(e - C_{shft})}{Z_t} \quad ; \text{ and } \quad S_{bot} = \frac{P}{A} + \frac{P(e - C_{shft})}{Z_b} \qquad \text{... (1)}$$

when the position of the resultant compression is exactly at centre line of the member $\left(\frac{h}{2}\right)$ i.e., $C_{shft} = e$. Then the stresses in concrete member at top and bottom fibre due to external Prestressing S_{top} were computed as $S_{top} = \frac{P}{A}$; and $S_{bot} = \frac{P}{A}$ ... (2)

On this basis of experimental results, it was assumed that stress-increase will occur only after decompression takes place since stress-increase in external tendons bounds by deflection of the member (as deflection compatibility controls the analysis). Moment of inertia for original section I was used for the analysis of externally pre stressed (retrofitted) member at stage before decompression, as there is no crack opening before decompression. Whereas, Moment of Inertia for transformed section I_{trp} was used for the analysis of externally pre stressed (retrofitted) member at stage after decompression, as there is crack opening after decompression. When the position of resultant compression is above the centre line of the member, i.e., $0 < e < C_{shft}$, the decompression used to happen, and therefore tension creates at bottom fiber and compression creates at top fiber of the concrete member. Therefore,

$$S_{top} = \frac{P}{A} + \frac{P(C_{shft} - e)y_t}{I_{trp}} \quad ; \text{ and } S_{bot} = \frac{P}{A} - \frac{P(C_{shft} - e)y_b}{I_{trp}} \qquad \text{... (3)}$$

Deflection

When the member not reached to the decompression stage, i.e., $0 < w < w_{dc}$, the deflection of the strengthened beam y_p was computed as $y_p = -\frac{Pe_{new}\,L^2}{12E_{cp}\,I}$. When the applied load reached the decompression stage, but not reached the further distressing stage, i.e., $w_{fd} > w \geq w_{dc}$, then the y_p was computed as

$$y_p = -\frac{Pe_{new}\,L^2}{12E_{cp}\,\emptyset_1 I_{trp}} + kL^2\left[\frac{M_{dc}}{E_{cp}\,I} + \frac{M_p - M_{dc}}{0.85E_{cp}\,\emptyset_1 I_{trp}}\right] + \frac{5}{384}\frac{w_d L^4}{E_{cp}\,\emptyset_1 I_{trp}} \qquad \text{... (4)}$$

When the applied load reached decompression stage and also the further distressing stage, i.e., $w \geq w_{fd} > w_{dc}$, then the deflection y_p was computed as

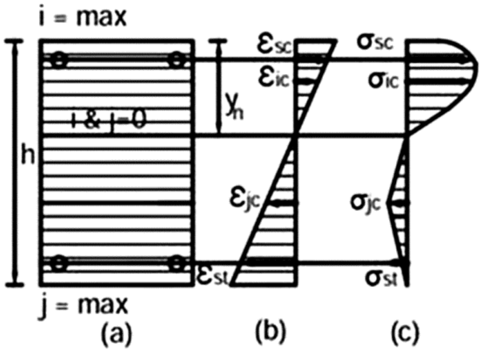
$$y_p = -\frac{Pe_{new}\,L^2}{12E_{cp}\,\emptyset_2 I_{trp}} + kL^2\left[\frac{M_{dc}}{E_{cp}\,I} + \frac{M_p - M_{dc}}{0.85E_{cp}\,\emptyset_2 I_{trp}}\right] + \frac{5}{384}\frac{w_d L^4}{E_{cp}\,\emptyset_2 I_{trp}} . \qquad \text{... (5)}$$

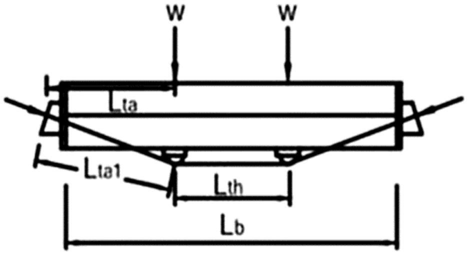
Where $I_{trp} = \left(\frac{M_{dc}}{M_p}\right)^3 I + \left[1 - \left(\frac{M_{dc}}{M_p}\right)^3\right] I_{crack}$; and $I_{crack} = \frac{b.d_{np}{}^3}{3} + m.A_{st}\left(d - d_{np}\right)^2$

$\emptyset_1$ is the reduction factor for moment of inertia of transformed section for the stage from load at decompression to load at further distress; and $\emptyset_2$ is the reduction factor for moment of inertia of transformed section for the stage from load at further distress to the load at ultimate.

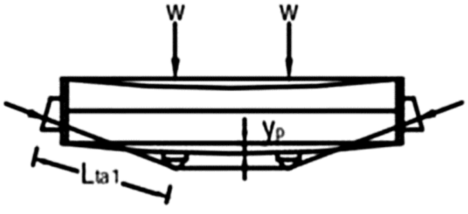
Stress in external tendons at ultimate state

Total length of tendon in between anchorages (considering straight) is shown in Figure 3d, ie., $L_t = L_b + 2t_p$. Total length of tendon without deflection





d) Without deflection



e) With deflection

Fig. 3 — Strain and stress distribution in components of RC beam, and shape of retrofitted RC beams before and after deflection

(considering deflection at one of the deviators) is shown in Figure 3d. When $< w_{dc}$, the $L_{tr1} = (2.L_{ta1}) + L_{th}$

Where L_{ta1} is the length of the inclined portion of tendons; L_{ta} is the horizontal length of tendon from end plate to the centre of deviator; L_{th} is the length of tendon of horizontal portion at mid span between two deviators; Total length of tendon with deflection (considering deflection at one of the deviators) is shown in Figure 3e and calculated:

When $\geq w_{dc}$, $L_{tr2} = (2.L_{ta2}) + L_{th}$; and

$$L_{ta2} = \sqrt{\left(e + y_p\right)^2 + {L_{ta}}^2}$$

Where L_{ta2} is the length of the inclined portion of tendons (considering with deflection); Change in length of tendon was computed as $dL_t = L_{tr2} - L_{tr1}$; Strain in tendons was computed as $\varepsilon_t = \frac{dL_t}{L_{tr1}}$; Stress in tendons was computed as $\Delta f_{ps} = \varepsilon_t E_{ps}$. Therefore, stress at ultimate in external tendons was computed, in ACI form as follows:

$$f_{ps} = f_{pe} + \Delta f_{ps} \qquad \text{... (6)}$$

Where $\Delta f_{ps} = \varepsilon_t E_{ps}$

Discussion

The cracked RC beam section was modeled by sectional analysis. The reduction in compressive strength due to crack in concrete was evaluated by compression softening coefficient β which were computed for EPS-B7 and EPS-B9 as 0.93 and 0.897 respectively. They were incorporated into the analytical model for post-retrofitting behaviour. The retrofitted beam exhibited three stages of behaviour viz., i) from the effective pre stress to the load at decompression, w_{dc} ii) from the load at decompression w_{dc} to the load at further distress w_{fd} and iii) from the load at further distress w_{fd} to the load at ultimate w_u. It was observed from the model that the neutral axis shifts towards top when the beam deforms and deflects, and the shifted neutral axis again shifts towards bottom due to the retrofitting. The shifted neutral axis due to retrofitting was named as d_{np} , which was computed using regression method. The d_{np} for EPS-B7 and EPS-B9 were 95.00 mm and 85.00 mm respectively. It was necessary to reduce the moment of inertia for transformed section, I_{trp}, to predict the ultimate behaviour. Therefore, reduction factors for I_{trp} for second stage and third stage were introduced as $\emptyset_1$ and $\emptyset_2$ respectively, which were computed by regression method. For beam EPS-B7, there was no need to reduce the I_{trp} and therefore the reduction factors $\emptyset_1$ and $\emptyset_2$ were 1.00 and 1.00 respectively. The reduction factors $\emptyset_1$ and $\emptyset_2$ for beam EPS B9 were 1.00 and 0.84 respectively. The ratio $\frac{\emptyset_1}{\emptyset_2}$ for EPS B7 and EPS B9 were 1.00 and 1.19 respectively. The model was compared with the test results and the Moment-Deflection relation for EPS-B7 and EPS-B9, which are shown in Figure4 Retrofitting by external Prestressing has

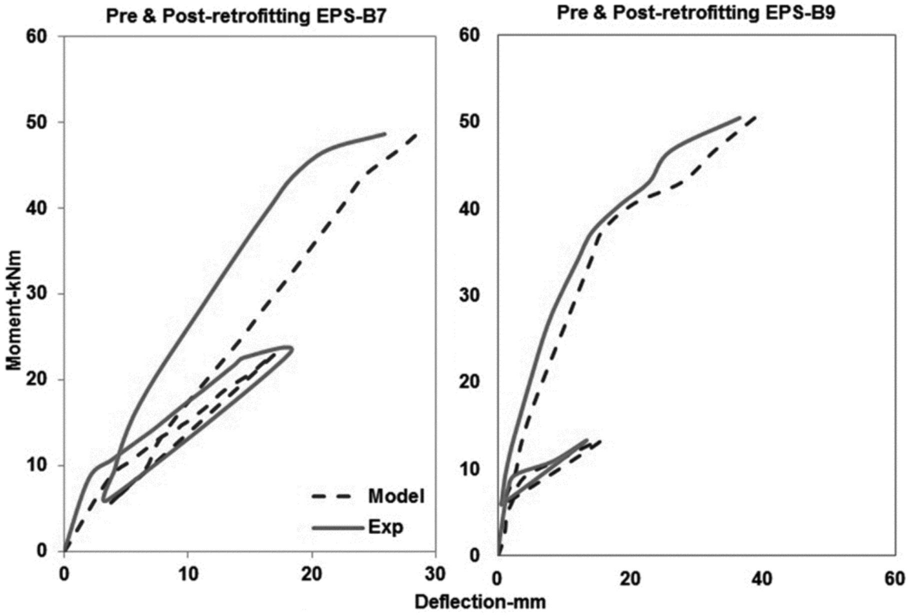


Fig. 4 — Moment-Deflection relation for specimens EPS B7 and EPS B9

increased the ultimate flexural load carrying capacity by 53 % and 59 % for EPS-B7 and EPS-B9 respectively.

Conclusions

Retrofitting of distressed RC beams by external Prestressing has increased the ultimate flexural load capacity by 59 %. Deflection recovery was observed as maximum of 86 %. 10% loss of pre stress due to friction at deviators was observed. RC beams retrofitted by external tendons could be analysed by applying compatibility between deflection of concrete member and strain-increase in external tendons beyond effective Prestressing stage. Retrofitted beams exhibited three stages of behaviour viz., i) from the effective Prestressing stage to the load at decompression, w_{dc} ii) from the load at decompression w_{dc} to load at further distress w_{fd} and iii) from the load at further distress w_{fd} to load at ultimate w_u. Stress-increase in external tendons for strengthened RC beams Δf_{ps} is at the stage from decompression to the ultimate.

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