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ORIGINAL CONTRIBUTION

Retrofitting of Distressed Post-tensioned Concrete Members by External Post-tensioning

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Abstract Many of the existing prestressed concrete bridges are in distressed condition in India and abroad. Deterioration occurs due to various reasons. This has considerably reduced the load-carrying capacity of many prestressed concrete (PSC) bridges. Therefore, it is necessary to improve the retrofitting solutions to recover the load-carrying capacity that is lost due to distress. One of the prime techniques that is being used for retrofitting of existing bridges is external post-tensioning. However, behaviour of the retrofitted PSC members is still not understood in depth. It is intended to report the behaviour of retrofitted post-tensioned concrete specimens by external post-tensioning, on which distress was induced by the combined effect of loss of prestress and fatigue deformation before retrofitting. As a result of retrofitting, the ultimate load-carrying capacity has increased by 33% with reference to the fully prestressed control beam specimen. The ductility is observed as 94% of the ductility of the control specimen.

Keywords External post-tensioning · Retrofitting · Concrete member · Flexural behaviour · Fatigue · Cyclic · Stress in tendons

Introduction

There are a number of highway and railway bridges, which have been distressed in India and abroad. They are distressed due to various reasons like loss of prestress, ageing effects, increase in volume of traffic, corrosion in rebars and prestressing steel, poor quality of construction, improper functioning of bearings and design deficiencies. External post-tensioning is being widely used successfully for retrofitting of distressed concrete bridges around the world. However, some of the existing bridges retrofitted by external post-tensioning have experienced distress even after retrofitting. This made bridge engineers to examine the efficacy of the technique and its performance in post-retrofitting life. Therefore, post-retrofitting behaviour of the members that are retrofitted by external post-tensioning needs to be studied.

One of the major sources of distress in a prestressed concrete bridge is the loss of prestress. It reduces the stiffness of the girders considerably and hence reduces the load-carrying capacity of the bridges. Three distressed bridges in Italy, namely A3 Motorway Viaduct, Stupino and Ruiz Viaducts, and E45 Viaducts, had reported that the loss of prestress was upto 60%. These bridges were strengthened by external post-tensioning [1]. Zuari bridge and Sharavathi bridge of India indicated loss of prestress of 20% and 25%, respectively, and were strengthened using the same technique [2]. Hvozdnica bridge across Vah river in Slovakia was deteriorated, and later retrofitted by external prestressing showed improved load-carrying capacity from 26 to 31 tonnes [3]. Evaluation of effective prestress in tendon of the dismantled Italian Motorway Bridge girder after serving 40 years found that the loss of prestress is ranged from 28 to 34% [4]. These informations reveal that the loss of prestress occurs in real-life bridges is in the range of 15% to 60%. In case of laboratory investigations, simulation of distress is an important phenomenon. Although there are various distresses which are occurring in real-life bridges, it is difficult to simulate all the distresses in laboratory investigations. However, simulating the distress that is relevant to the practical cases and then retrofitting could give good results regarding post-retrofitting

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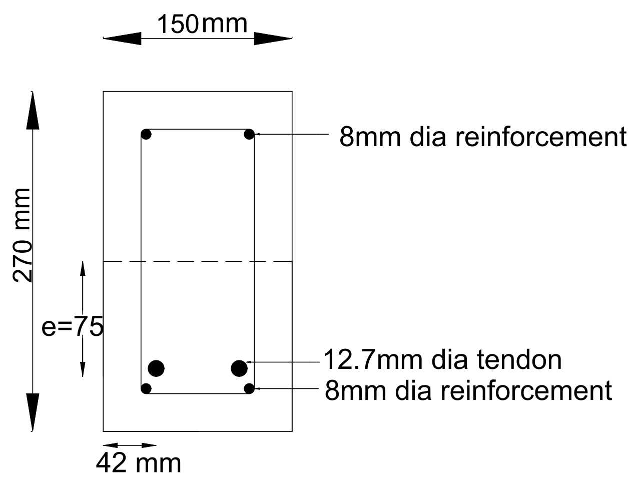


Fig. 1 Reinforcement detailing of the section

behaviour. Experimental investigations of reinforced, prestressed, and partially prestressed concrete beams, which were induced distress with monotonic loading and fatigue loading, and then strengthened by external prestressing, and again loaded with monotonic loading till failure, reported that flexural strength of the beams had increased by up to 146% [5]. Experiments on prestressed concrete beams which were distressed only by monotonic load, then strengthened by external post-tensioning and then tested up to failure reported that they performed well in post-retrofitting behaviour in improving stiffness and ductility [6–8]. Also, loss of prestress due to friction at deviators of trapezoidal tendon profile is reported as 10% [8]. In some investigations, distresses were made only by monotonic load and then unloaded before retrofitting by external post-tensioning [6] and [7]. In such cases, the prestressing action regains the deflection produced by the monotonic load, and hence no distress is induced. Secondly, the real bridge girders are retrofitted, while super imposed dead loads, namely handrails, deck slab and other components of superstructure, are acting on the bridge. Therefore, removal of this load fully and then retrofitting are not reflecting the practical cases. Also, monotonic load does not produce permanent deflection in prestressed concrete members. Even if a PSC member is loaded beyond the elastic range, the monotonic load cannot give permanent deflection. In view of this, the studies presented in this paper simulated the distress by loss of prestress and fatigue deformation, and retrofitting by external post-tensioning, while super imposed dead load is acting on the girder.

Increase in stress of internal unbonded or external tendons Δf_{ps} is the parameter that is influencing the ultimate flexural behaviour of any post-tensioned concrete members. Since the analysis of member is a member dependent, the analysis by section dependent is ruled out. Equations for stress at ultimate in unbonded tendons, developed by various researchers, are in the form: $f_{ps} = f_{pe} + \Delta f_{ps}$. Although the equation is developed for analysing new post-tensioned concrete members, it can be applied for retrofitted members if the untensioned tensile steel is not yielded before retrofitting [9]. The untensioned tensile steel of tested specimens presented in this paper had also not yielded. Therefore, Eq. (3) for calculating the stress increase in external tendons Δf_{ps} for strengthening case [9] is used for validating the test results presented in this paper. Another model that has predicted the behaviour of distressed RC members by external

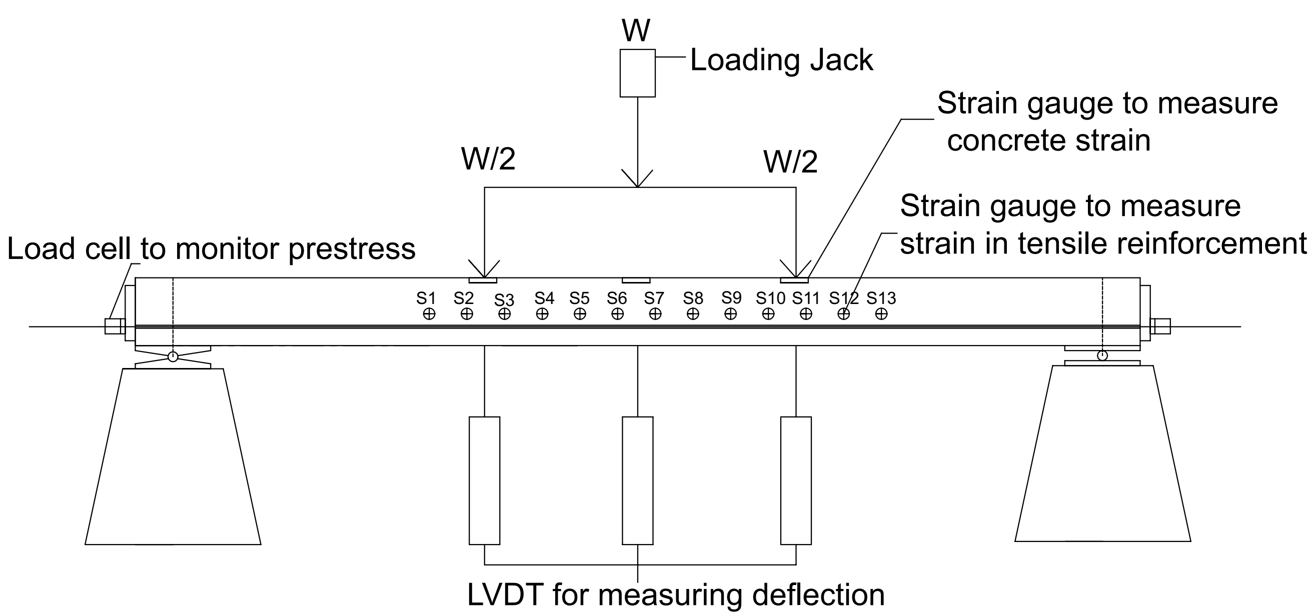


Fig. 2 Schematic sketch of the test setup along with instrumentation details

Table 1 Test results of the specimen CB-1

Static load: CB-1	
P (kN)	*y* (mm)
0	0
10	1.1
20	2.2
30	3.4
40	4.7
50	6.3
60	8.3
70	10.9
80	15.1
90	20.5
100	26.4
110	36.9
120	50.6
124.05	58.1

P load, *y* deflection

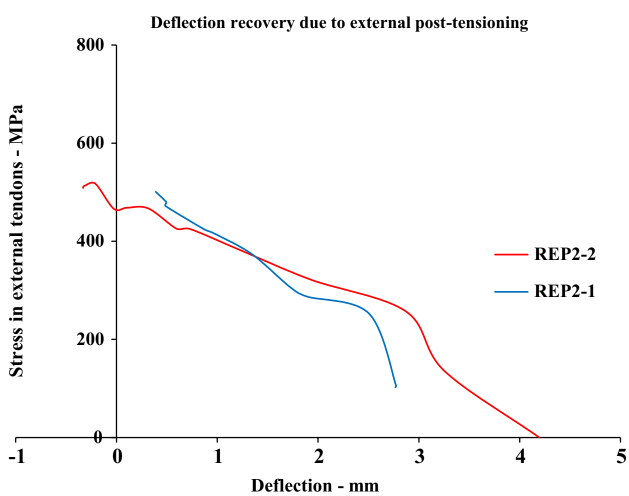


Fig. 3 Deflection recovery due to external post-tensioning

post-tensioning suggested that the Δf_{ps} is occurred from decompression to yielding of the untensioned reinforcement [10]. The conclusion that Δf_{ps} is directly related to the formation of plastic hinge [11], is similar to the observation made at the investigation [10]. An equation was developed to predict Δf_{ps} by incorporating an expression for evaluating the equivalent plastic hinge length [12]. Test results suggested that the stress increase in external tendons Δf_{ps} is approximately 30 to 50% of the effective prestress f_{pe} at the ultimate load [13]. Configuration of deviators, tendon profile and the inelastic deflection have influenced the second-order effect (variation in eccentricity) [14]. Also, the tendon slip, frictional resistance at deviators, second order effects and ultimate capacity of the members are inter-related [15].

The literature review informed about the issues, namely, range of loss of prestress occurs in bridges, prediction of stress increase in tendons and second-order effects. It is observed that few investigations have studied the behaviour of retrofitted members by external post-tensioning, after inducing the distress that reflects the real-life bridges. In view of this, this paper presents the behaviour of retrofitted post-tensioned concrete beam specimens by external post-tensioning, which were distressed by loss of prestress and fatigue deformation before retrofitting.

Experimental Investigation

Casting of Specimens

The materials used for the experiment consist of concrete with M45 grade of concrete, untensioned steel of Fe 415 grade and post-tensioning strand of 7-ply 12.7 mm diameter. PSC beam specimens of 3.74 m span with the section size of 150 mm × 270 mm were cast. The reinforcement cage was made by providing 2 numbers of 8 mm diameter bars in compression zone and the same in tension zone. 0.25% of cross sectional area has been provided as tensile reinforcement. The shear reinforcement consists of double-legged stirrup using 8 mm diameter bars. Figure 1 shows the reinforcement detailing of the section. Five-millimetre electrical resistance strain gauges were used for observing strain of tensile reinforcement during the test. To ensure this, strain gauges were pasted in the tensile reinforcement at 150 mm spacing in flexural zone and spread of plasticity region.

Testing of Control Specimens CB-1 and CB-2

Specimen CB-1 is a control beam specimen, a fully prestressed one, was subjected to monotonic static load up to failure. Specimen CB-2 is also a control beam specimen distressed with 20% loss of prestress, which was tested under high cycle fatigue load up to failure. Results of CB-2 were used for deciding number of fatigue load cycles for inducing fatigue deformation in specimens meant for retrofitting, namely, REP2-1 and REP2-2. The schematic sketch of test setup along with instrumentation details is shown in Fig. 2.

Testing of Retrofitted Specimens REP2-1 and REP2-2

The specimens REP2-1 and REP2-2 were schemed to simulate distress with 20% loss of prestress plus fatigue deformation, then to retrofit with external post-tensioning and then to test the retrofitted specimens by static monotonic load up to ultimate.

Normally, bridges are retrofitted, while super imposed dead loads of bridge girder, namely deck slab, hand rails

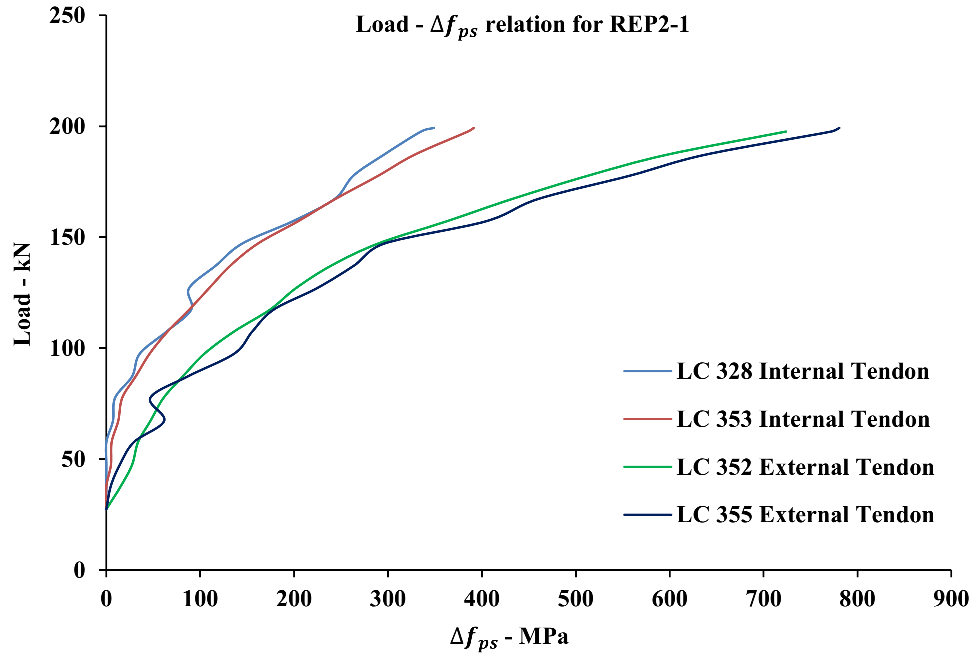


Fig. 4 Stress increase in internal and external tendons for REP2-1

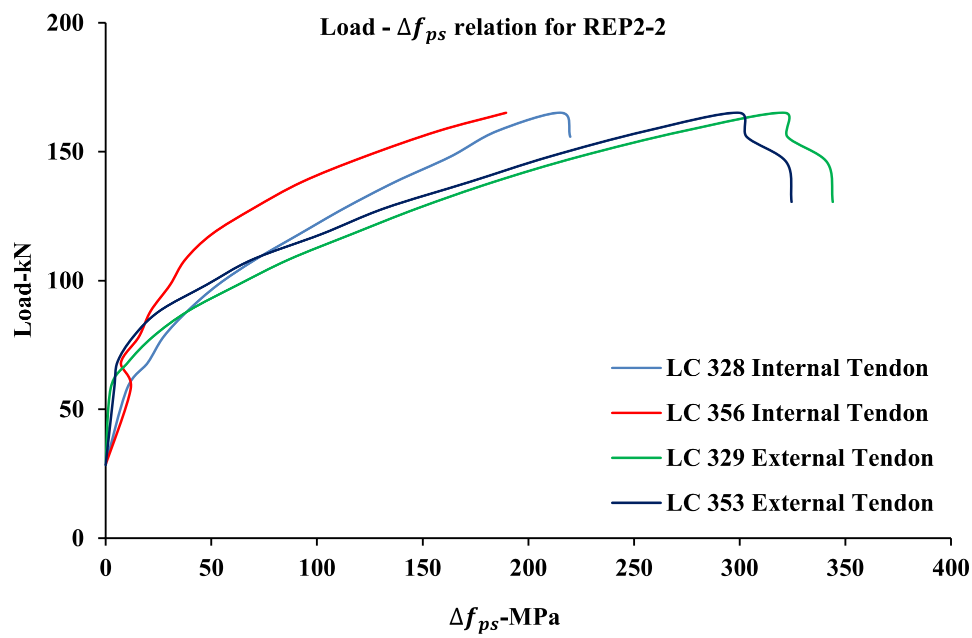


Fig. 5 Stress increase in internal and external tendons for REP2-2

and other loads on the bridges, are acting on the bridges. Therefore, retrofitting was carried out, while super imposed dead load was acting. The prestressing force for retrofitting was decided based on the stiffness reduction and deflection. Accordingly, the retrofitting by external post-tensioning was carried out using Hydraulic Jack of 20 tonnes capacity. Two numbers of 7 ply-12.7 mm diameter, one on each side of the specimen, were stressed with trapezoidal tendon profile at the eccentricity of 210 mm. Two numbers of deviators were fixed in the flexural region to make the trapezoidal tendon profile.

Results and Discussion

The control beam specimen CB-1 is a fully prestressed concrete specimen, which was post-tensioned with an effective

Fig. 6 Failure of the retrofitted specimen REP2-2

prestress of 1140 MPa by straight tendon profile at an eccentricity of 75 mm. It was tested by monotonic static load and failed at 124.05 kN by concrete crushing at the extreme compressive fibre with a maximum deflection of 58.1 mm. The test results are given in Table 1. The stress in post-tensioning tendons f_{ps} had reached 1470 MPa at the time of failure. The stress increase in tendons Δf_{ps} was 330 MPa.

The control beam specimen CB-2 was stressed to the effective prestress of 920.5 MPa, which induced 20% loss of prestress when compared to the specimen CB-1. It means that only 80% of the effective prestress of CB-1 was applied to the CB-2. It was tested under high cycle fatigue load. Failure of the beam had occurred by breaking of untensioned tensile reinforcement at 165,418 cycles, followed by concrete crushing in the compression fibre. The maximum deflection at failure was 26 mm. The results of CB-2 were used to decide the number of fatigue load cycles to be given to REP2-1 and REP2-2 for inducing fatigue deformation/distress. Accordingly, it was decided to apply 110,000 cycles for inducing distress.

Behaviour of Retrofitted Specimens REP2-1 and REP2-2

In the specimens REP2-1 and REP2-2, distress by 20% loss of prestress and 110,000 high cycle fatigue deformation was induced and then retrofitted by external post-tensioning. Retrofitting was done, while the super imposed dead load of the bridge girder was acting. 25% of the ultimate load of the specimen was given as super imposed dead load. External post-tensioning had recovered the deflection to 0.5 mm and − 0.35 mm (upward) for REP2-1 and REP2-2, respectively, are shown in Fig. 3. Loss of prestress in external tendons due to friction at deviators is observed as 15%. It is to mention that it was intended to see the difference in post-retrofitting behaviour for two cases, namely i) removal of super imposed dead load after the retrofitting and then tested under static load up to failure (REP2-1); and ii) without removing the super imposed dead load after the retrofitting and tested by static load up to failure (REP2-2). Accordingly, the super imposed dead load was removed after retrofitting, and the specimen REP2-1 was tested from zero loading up to ultimate. For another specimen REP2-2, the super imposed dead load was not removed after retrofitting, and the specimen REP2-2 was tested from retrofitting position (from the load 27 kN) to the ultimate.

For the specimen REP2-1, the Δf_{ps} for internal tendons is 349.10 MPa and 391.3 MPa for LC 328 and LC 353 respectively, and Δf_{ps} for external tendons is 745.9 MPa and 780 MPa for LC 352 and LC 355 respectively, shown in Fig. 4. The stress increase in external tendons had occurred between decompression and yielding of untensioned tensile steel. It is observed that the stress increase in external tendons is 2 times more than that of internal tendons. The specimen REP2-1 failed at 199 kN with 57 mm deflection

Table 2 Test results of inducing fatigue distress for the specimen REP2-2

Static load up to 65 kN		Inducing distress by fatigue deformations													
		Cycle 35		Cycle 5000		Cycle 20,000		Cycle 40,000		Cycle 60,000		Cycle 80,000		Cycle 110,000	
P (kN)	*y* (mm)	*P* (kN)	*y* (mm)	*P* (kN)	*y* (mm)	*P* (kN)	*y* (mm)	*P* (kN)	*y* (mm)	*P* (kN)	*y* (mm)	*P* (kN)	*y* (mm)	*P* (kN)	*y* (mm)
0	0	65	15.6	65	16.8	65	17.3	65	17.2	65	17.6	65	17.7	65	17.9
10	1.4	55	12.7	55	13.6	55	13.9	55	13.8	55	14.1	55	14.4	55	14.6
20	2.7	45	9.3	45	9.8	45	10.1	45	10.1	45	10.4	45	10.6	45	10.7
30	4.1	35	6.7	35	7.0	35	7.4	35	7.3	35	7.5	35	7.6	35	7.8
40	5.7	27	5.3	27	5.6	27	6.0	27	5.8	27	6.1	27	6.4	27	6.5
50	7.8	35	6.6	35	6.9	35	7.3	35	7.2	35	7.6	35	7.8	35	7.9
60	11.2	45	8.8	45	9.6	45	10.2	45	10.0	45	10.3	45	10.5	45	10.6
65	15.0	55	12.4	55	13.2	55	13.8	55	13.8	55	14.0	55	14.1	55	14.2
		65	15.6	65	16.8	65	17.3	65	17.2	65	17.6	65	17.7	65	17.9

P load, *y* deflection

Table 3 Test results of the retrofitted specimen REP2-2

Deflection recovery due to retrofitting		Static load: retrofitted specimen REP2-2	
P (kN)	*y* (mm)	*P* (kN)	*y* (mm)
27	4.2	27	−0.33
27	3.25	30	−0.2
27	2.87	40	1.1
27	1.93	50	2.4
27	1.25	60	3.7
27	0.73	70	5.1
27	0.6	80	6.9
27	0.32	90	8.9
27	0.1	100	11.2
27	−0.02	110	13.8
27	−0.2	120	16.8
27	−0.3	130	19.9
27	−0.33	140	23.3
		150	27.3
		160	32.0
		165	43.3

P load; *y* deflection

by concrete crushing in compression fibre. This reveals the occurrence of plastic hinge at the ultimate state. Therefore, the member exhibited ductility in the post-retrofitting behaviour. The curvature ductility of REP2-1 and CB-1 is 1.308 and 1.728, respectively, and this observes that the REP2-1 shows ductility 76% of that of the specimen CB-1.

For the specimen REP2-2, the Δf_{ps} for internal tendons is 219.8 MPa and 189.4 MPa for LC 328 and LC 356 respectively, and Δf_{ps} for external tendons is 324.6 MPa and 344.1 MPa for LC 353 and LC 329 respectively, shown in Fig. 5. Like REP2-1, the stress increase in external tendons was 1.8 times more than that of internal tendons. The retrofitted specimen REP2-2 failed at 165 kN by concrete crushing in extreme compressive fibre, with a maximum deflection of 43.3 mm as shown in Fig. 6. The results for inducing distress by fatigue deformations from 35 cycles to 110,000 cycles are given in Table 2. Test data for a full loop of the corresponding cycle are given. A full loop consists of starting from maximum load, reaching minimum load and again coming back to maximum load. The results of deflection recovery due to retrofitting and testing of the retrofitted specimen REP2-2 by static monotonic load are given in Table 3. The behaviour of the specimen REP2-2 from inducing distress, retrofitting and after retrofitting is shown in Fig. 7. The specimen REP2-2 has increased the ultimate load carrying capacity by 33% more than that of control beam CB-1. The member exhibited ductility in the post-retrofitting behaviour. The curvature ductility of REP2-2 is calculated as 1.628, which is 94% of the ductility of the fully prestressed control specimen CB-1. These observations coincide with the conclusion of a previous work [6] that the precracked beams after strengthening and the uncracked strengthened beams are analytically same, if the tensile reinforcement has not yielded before strengthening.

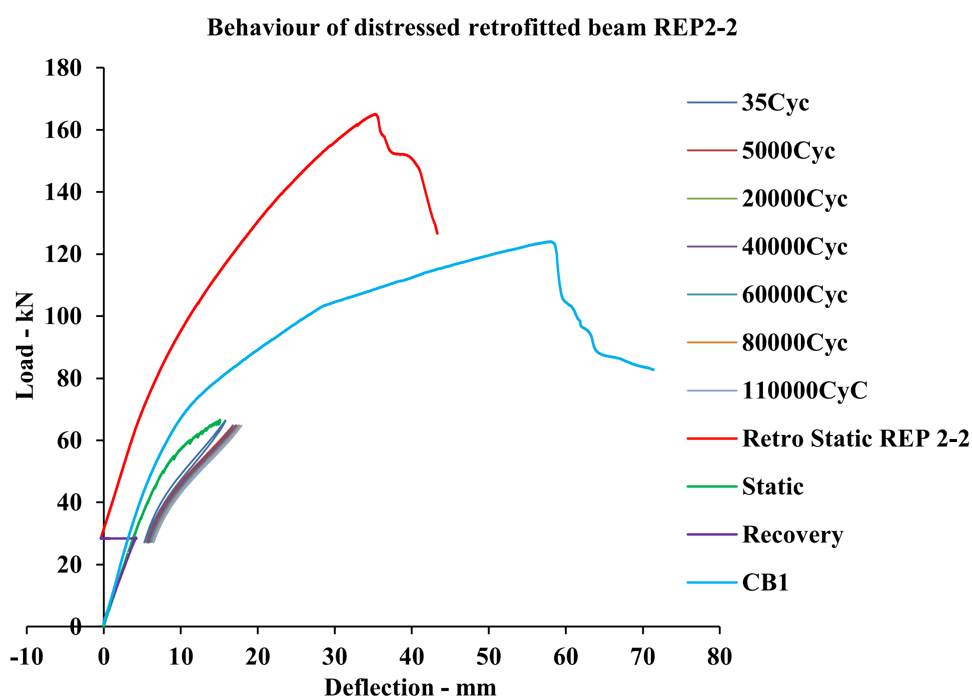


Fig. 7 Load–deflection behaviour of the retrofitted specimen REP2-2

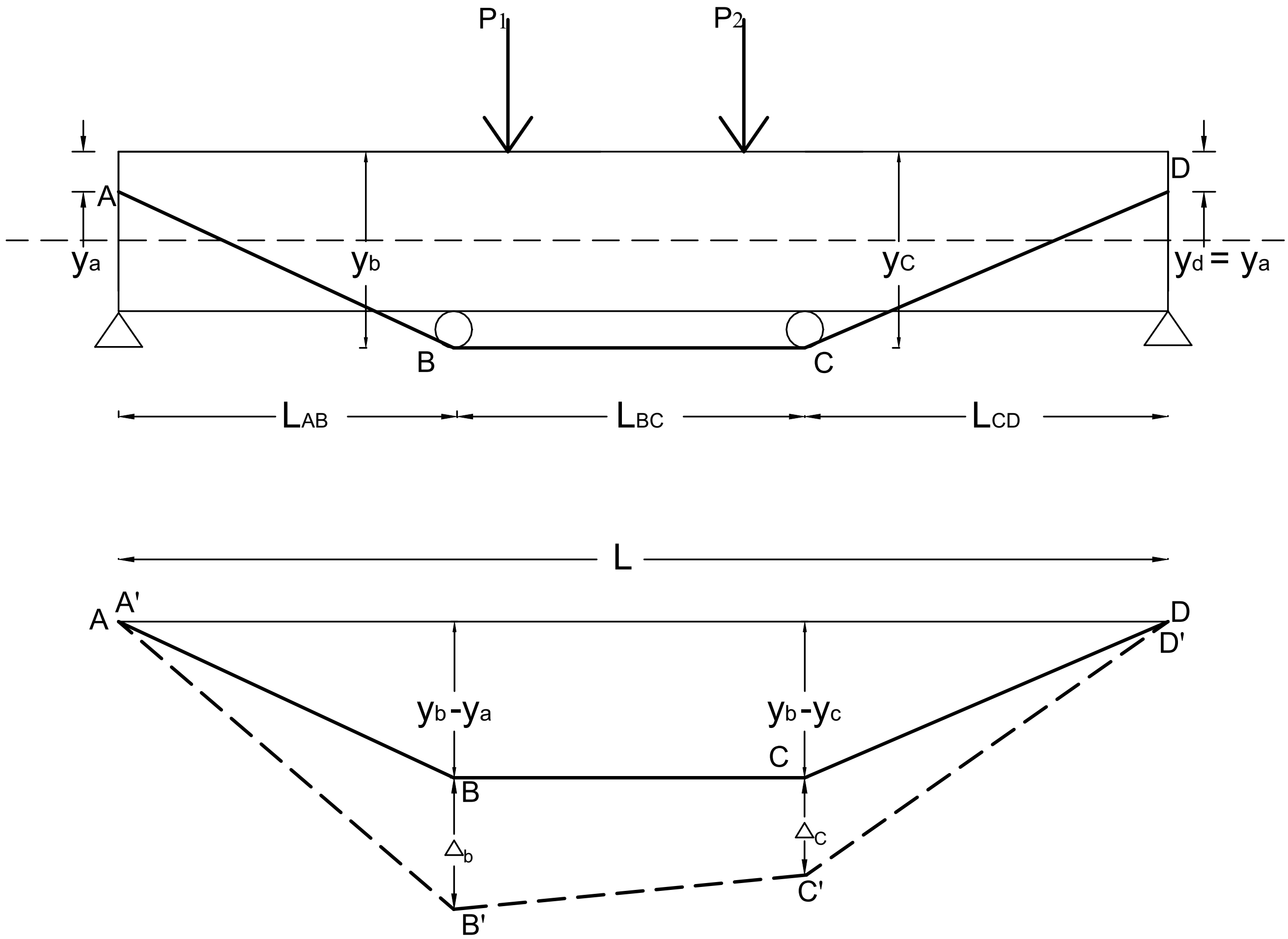
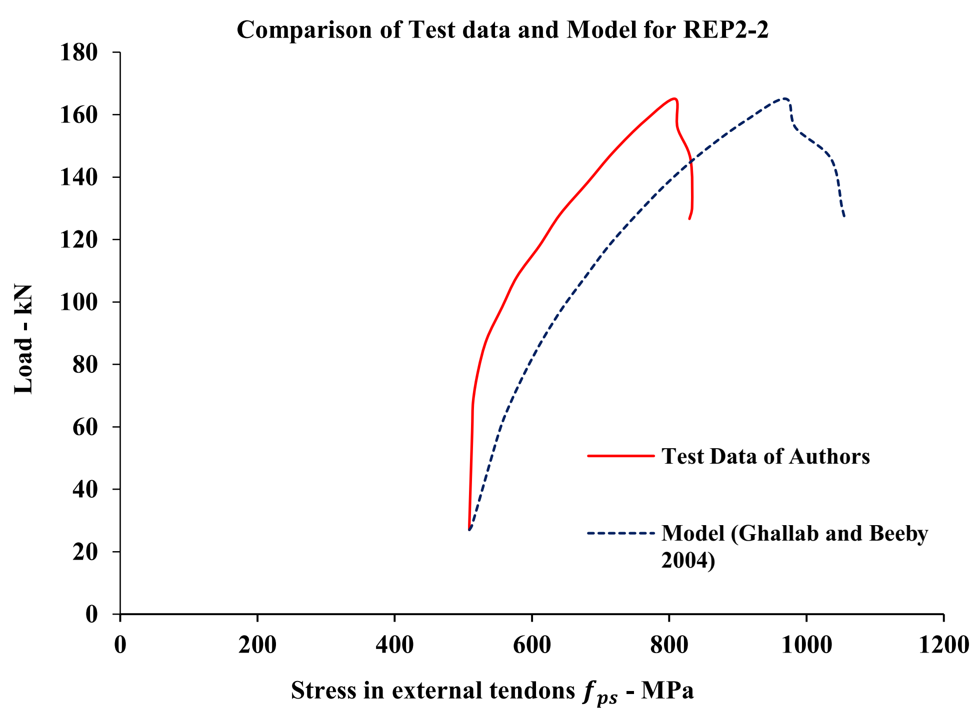


Fig. 8 Illustration corresponds to the analytical model

Fig. 9 Comparison of f_{ps} (Exp) with f_{ps} (model) for REP2-2



Comparison of Test Data with Analytical Model

It is well known that the trapezoidal tendon profile is proved as efficient one for retrofitting by external post-tensioning and reduces the effects due to second-order effects. Since the test specimens reported in this paper are retrofitted using trapezoidal tendons, the analytical model of Ghallab and Beeby 2004 [9] was selected for comparing with test results. The illustration corresponds to the analytical model is shown in Fig. 8.

$$\text{Total initial length of tendon} = L_t = AB + BC + CD \tag{1}$$

$$L_t = \sqrt{L^2AB + (y_b - y_a)^2} + \sqrt{L^2BC + (y_b - y_c)^2} + \sqrt{L^2CD + (y_c - y_d)^2}$$

Total length of the external tendon after loading $= L_t^* = A'B' + B'C' + C'D'$.where

$$A'B' = \sqrt{L^2AB + \left(y_b - y_a + \Delta_b\right)^2}$$
$$B'C' = \sqrt{L^2BC + \left(y_b + \Delta_b - y_c - \Delta_c\right)^2}$$
$$C'D' = \sqrt{L^2CD + \left(y_c - y_d + \Delta_c\right)^2}$$

$$\text{The elongation of the tendon} = \Delta L = L_t^* - L_t \tag{2}$$

$$\text{Total tendon strain} = \varepsilon_{\text{ps}} = \varepsilon_{\text{pe}} + \Delta\varepsilon_{\text{ps}} = \frac{f_{\text{pe}}}{E_{\text{ps}}} + \frac{\Delta L}{L_t} \tag{3}$$

It is observed that the results of the model are varied 13% with test results of load vs stress in external tendons (f_{ps}), for specimen REP2-2. Also, the f_{ps} of model and that of experiment data is compared, which is shown in Fig. 9. The results of the specimen REP2-1 observed over estimation of the ultimate capacity due to removal of super imposed dead load after retrofitting. Because of this reason, the comparison of REP2-1 with analytical model is not reported.

Conclusions

1. The post-tensioned concrete beam specimen distressed with 20% loss of prestress and fatigue deformation and retrofitted by external post-tensioning has enhanced the load-carrying capacity by 33% when compared to the fully prestressed control specimen CB-1. The ductility of the retrofitted specimen is 94% of that of the CB-1.
2. The retrofitted beam specimen, in which the super imposed dead load was removed after retrofitting, and then tested from zero loading, has overestimated the ultimate capacity of the retrofitted beam (REP2-1). Therefore, the super imposed dead load should not be removed before testing of the retrofitted beam.
3. Although the specimens were distressed with 20% loss of prestress plus 110,000 high cycle fatigue load cycles before retrofitting, they behaved almost in a similar way of non-distressed beams after retrofitting. Because the untensioned tensile steel is not yielded, the retrofitted members ensured an improved ultimate capacity, ductility and occurrence of plastic hinge before failure.
4. Loss of prestress in external tendons due to friction at deviators is observed as 15% for trapezoidal tendon profile. Therefore, loss of prestress due to friction at deviators should be accounted in the design of retrofitting scheme. Because of retrofitting by external post-tensioning, no loss of prestress was observed in internal tendons.
5. Stress increase in unbonded tendons Δf_{ps} for new post-tensioned concrete members started after the yielding of tensile steel. In case of retrofitted members, it started between decompression and yielding of tensile steel. Stress increase in external tendons in retrofitted members was observed as 1.8 times that of internal tendons.

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Declarations

Conflict of interest There is no competing interest in this manuscript.

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