Numerical and experimental investigations of single span prestressed concrete beams

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Modern structural engineering tends to progress towards more economical structures through gradually improved methods of design and the use of higher strength materials. Such developments are particularly important in the field of reinforced concrete; the limiting features of ordinary reinforced concrete have been largely overcome by the development of prestressed concrete. The post-tensioning technique has been commonly used in the construction field because it facilitate the analysis and design of structures widely applicable for many type structures. In this paper the displacement behavior of single span prestressed concrete beams have been studied numerically and experimentally. Six beams were cast and experimented. The experimental results were compared with finite element method results. Using these data, friction and anchorage losses have been also calculated. It is observed that friction loss is almost constant but anchorage loss may vary considerably. Hence anchorage loss should be minimised for effective application of prestressing force.

1. INTRODUCTION

In ordinary reinforced concrete, consisting of concrete and mild steel as basic components, the compressive stresses are borne by concrete while tensile stresses are borne by steel. The concrete surrounding steel reinforcement does not take part in resisting the external forces since concrete is considered weak in tension. It simply acts as a bonding material. Thus only that portion of concrete, which lies above the neutral axis, is considered to be useful in resisting the external forces. This results in heavy section. In the case of prestressed concrete comprising of concrete and high tensile steel as basic components, both steel and concrete are stressed prior to the application of external loads. If such induced prestress in concrete is of compressive nature, it will balance the tensile stress produced in concrete surrounding steel due to external loads. Due to this, whole of the concrete can participate in resisting the external forces. Chen *et al* (2005) investigated The effective width of a concrete slab in steel–concrete composite beams prestressed with external tendons and concluded that prestressed with external tendons, the effective width of a concrete flange of a composite beam appeared slightly greater than the effective width when the beam was not prestressed. Özcan *et al* (2006) carried out experimental and finite element analyses of the steel fiber-reinforced concrete (SFRC) beams. The results obtained from the finite element and experimental analyses were compared and found in good match. Chung *et al* (2006) worked on the deflection estimation of a full scale prestressed concrete girder using long-gauge fiber optic sensors. It was demonstrated that long-gauge fiber optic sensors could provide the same accuracy with conventional sensors. Frederick *et al.* (2000) carried out experimental study of CFRP-prestressed high-strength concrete bridge beams. Fiber-reinforced polymer (FRP) tendons and reinforcing bars (rebar) were developed for use with concrete. FRP products are non-corrosive and lightweight when compared to traditional steel members. Zhang *et al* (2007) attempted experimental and theoretical studies on composite steel concrete box beams with external tendons. Sung *et al.* (2008) established stress–strain and deflection relationships of RC beam bonded with FRPs under sustained load Fiber-reinforced polymer (FRP) systems that had a strong resistance against long-term deformation. Padmarajaiah *et al.* (2000) attempted finite element assessment of flexural strength of prestressed concrete beams with fiber reinforcement. Influence of fibers on the concrete failure surface and stress–strain response of high strength concrete and the nonlinear stress–strain curves of prestressing wire and deformed bar were considered. Padmarajaiah *et al.* (2001) carried out flexural strength predictions of steel fiber reinforced high-strength concrete in fully and partially prestressed beam specimens. These studies mainly attempted to determine the influence of trough-shaped steel fibers in altering the flexural strength at first crack and check the load–deflection and moment–curvature characteristics, ductility and energy absorption capacity of the beams. Cattaneo *et al.* (2011) investigated the flexural behavior of reinforced, prestressed and composite self-consolidating concrete beams. The flexural behavior at service stage and at ultimate limit state was experimentally studied by means of four-point bending tests on six beams. Eythor *et al.* (2011) tested prestressed concrete beams with BFRP (basalt fibred reinforced polymer) tendons. The main findings were that the stiffness and bearing capacity of the beam increased relative to un-prestressed beams.

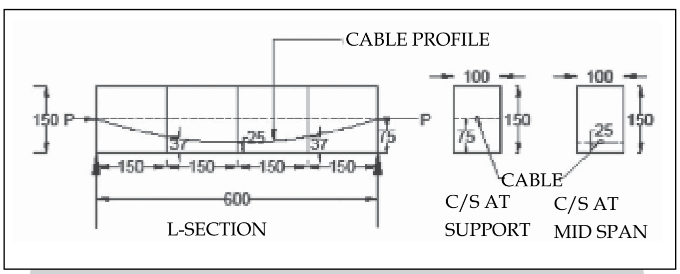

Figure 1. Cable profile and FE Model of A1, B1 and C1

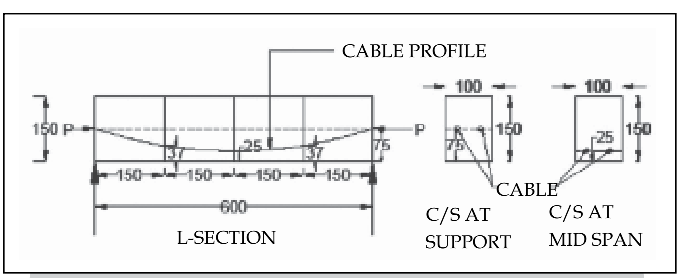

Figure 2. Cable profile and FE Model of A2, B2 and C2

In this paper numerical and experimental studies on single span prestressed concrete beams have been carried out. An inhouse developed FEM code was used for analysis purpose. By comparing the experimental and numerical results, friction and anchorage losses have been computed and results are critically analyzed.

2. EXPERIMENTAL & ANALYTICAL STUDIES

Prestressing system had been developed exclusively for this research work. A wooden mould of size 100 x 150 x 600 mm has been fabricated. The cable comprising of 3 number of 3 mm diameter (21.2 mm^2) HTS wires are used. Two categories of beams were casted, one with single strand and other with two strands. The beam A1, B1 and C1 fall in first category and beam A2, B2 and C2 fall in second category. The cable profiles of these beams are shown in Figure 1 and Figure 2. The Universal Testing Machine of capacity 400 kN as shown in Figure 3 was used for post tensioning of HTS wires. Since the UTM machine is vertically oriented, vertical post tensioning has been done in the beams, Wire locking barrels were used to anchorage the cable. The 3 mm thick steel plates

Figure 3. Vertical oriented beam for prestressing by UTM

Table 1. Material properties of beam and prestressing cable

Type	Cross sectional area(mm^2)	Density (kN/m^3)	Modulus of elasticity (GPa)
Concrete beam	15000	25	20
Strand	21.2	7830.19	200

having hole of 8 mm dia. to pass through tensioning cable were attached on both ends of the PSC beams. Selected proportion for M-35 grade concrete mix were designed as per IS code method. These beams were analytically analyzed for different prestressing force, loads and no of strands.

The properties of the materials that were used are given in Table 1. A detailed summary of the concrete beams that were tested is given in Table 2.

Three point loading test was conducted on all six beams in order to evaluate the deflection at mid span. A universal testing machine (UTM) was used to apply loading on each beam. In order to measure the deflection of beams, a dial gauge of least count 0.002 mm was installed at the mid span of each beam, as shown in Figures 4 to 9. The deflection of the beams obtained experimentally and numerically are given in Tables 3 to 8.

The load increment is taken 2 kN and it is applied on mid span section. Simply supported conditions are created for testing. The load displacement results from both methods are recorded and compared. The net deflection is also calculated using analytical formula given below.

$$\Delta net = \frac{5PeL^2}{48EI} - \frac{WL^3}{48EI} - \frac{5wL^4}{384EI}$$

where, P = Prestressing force in N

e = eccentricity of prestressing force in mm

L = span of the beam in mm

E = modulus of elasticity of concrete in N/mm^2

I = moment of inertia of beam about x-x axis in mm^4

W = point load at mid span on beam in N

w = dead load of beam in N/mm

3. NUMERICAL STUDIES

Numerical and experimental investigations of the six PSC beams have been carried out. For numerical analysis, an in-house finite element method based FORTRAN code PRESS2D (Akhtar *et al* 2008) has been used. Concrete is modeled as 9 node plane stress element and cable is modeled as 3 node bar element. There are 4 elements and 27 nodes in the FE model. As per IRC, coefficient of friction and Wobble effect are taken 0.17 and $2x10^{-6}$ respectively (Bapat *et al* 2010). FE model of various beams are shown in Figure 1 and Figure 2.

4. DETERMINATION OF LOSSES

The central deflection obtained by numerical (FEM) is compared with analytical counterpart. Prestress load in analytical formula is varied to match with FEM counterpart. The difference in the forces is due to friction loss. Similarly the central deflection obtained by experiment is compared with analytical counterpart.

Table 2. Specimens prestressed with strand tendon

Specimens	No. of strand	Prestressing force(KN)	Elongation of strand (mm)	Prestressing loss due friction in %	Prestressing loss due anchorage slip in %	Total losses in %
A-1	1	25.60	4.57	8.83	5.82	14.65
B-1	1	28.48	5.13	7.65	3.52	11.17
C-1	1	35.00	5.40	8.43	6.64	15.07
A-2	2	42.04	10.42	9.85	7.97	17.82
B-2	2	44.96	11.18	9.03	9.12	18.15
C-2	2	51.36	13.30	8.49	12.65	21.14

Figure 4. Measurement of deflections for PSC beam A1

Figure 5. Measurement of deflections for PSC beam B1

Figure 6. Measurement of deflections for PSC beam C1

Figure 7. Measurement of deflections for PSC beam A2

Figure 8. Measurement of deflections for PSC beam B2

Figure 9. Measurement of deflections for PSC beam C2

Prestress load in analytical formula is varied to match with experimental counterpart. The difference in the forces is due to total loss. The loss due to anchorage slip is found by the difference of total loss to friction loss. In this way friction and anchorage losses are calculated.

5. RESULTS AND DISCUSSIONS

Using above methodology testing of PSC beam A1 is done on applying prestressing force of 25.60 kN, For different loads corresponding deflections are obtained. The load deflection data considering total prestressing loss using FEM and experiment is given in Table 3 and plot is given in Figure 10. It can be observed that both the results are quite close to each other. The friction loss, anchor slip loss and total losses are calculated and given in Table 2.

Testing of PSC beam B1 is done on applying prestressing force of 28.48 kN, for different loads and corresponding deflections obtained. The load deflection data considering total prestressing loss using FEM and experiment is given in Table 4 and plot is given in Figure 11. Again, it can be observed that both the results are quite close to each other. The friction loss, anchor slip loss and total losses are calculated and given in Table 2.

Table 3. Deflections under various loads for beam A1

Load in kN	Numerical (FEM) deflection in mm	Experimental deflection in mm
0	0.0000	0.0000
2	0.0175	0.0200
4	0.0350	0.0400
6	0.0525	0.0560
8	0.0699	0.0740
10	0.0874	0.0900
12	0.1049	0.1080
14	0.1224	0.1260

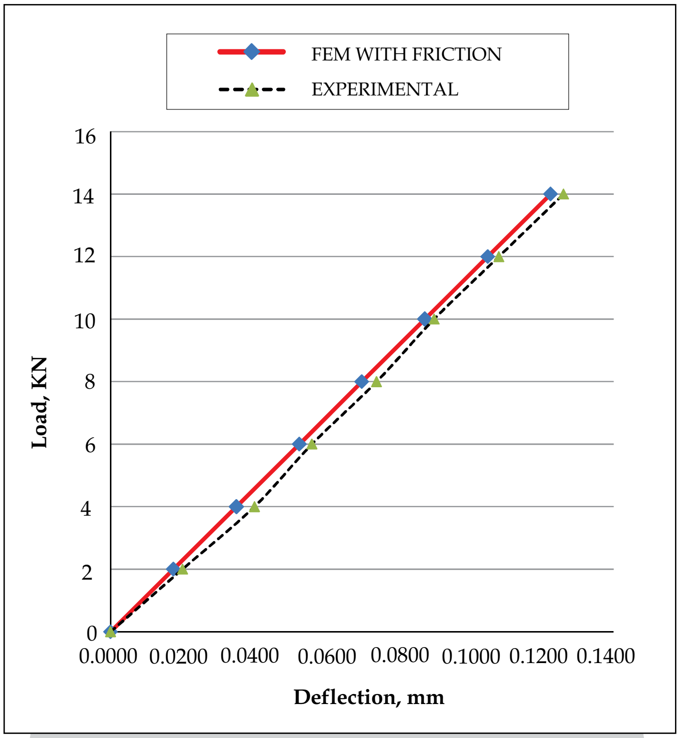

Figure 10. Load v/s deflection for beam A1

Table 4. Deflections under various loads for beam B1

Load in kN	Numerical (FEM) deflection in mm	Experimental deflection in mm
0	0.0000	0.0000
2	0.0175	0.0180
4	0.0350	0.0380
6	0.0525	0.0560
8	0.0699	0.0740
10	0.0874	0.0900
12	0.1049	0.1080
14	0.1224	0.1260

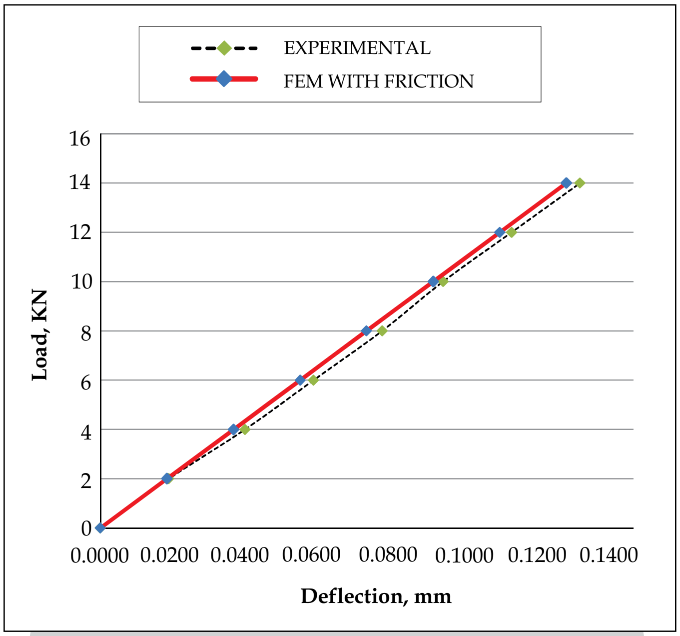

Figure 11. Load v/s deflection for beam B1

Testing of PSC beam C1 is done on applying prestressing force of 35 kN, for different loads and corresponding deflections obtained, The load deflection data considering total prestressing loss using FEM and experiment is given in Table 5 and plot is given in Figure 12. Again, it can be observed that both the results are quite close to each other. The friction loss, anchor slip loss and total losses are calculated and given in Table 2.

Testing of PSC beam A2 is done on applying prestressing force of 42.04 kN, for different loads and corresponding deflections obtained. The load deflection data considering total prestressing loss using FEM and experiment is given in Table 6 and plot is given in Figure 13. Again, it can be observed that both the results are quite close to each other. The friction loss, anchor slip loss and total losses are calculated and given in Table 2.

Table 5. Deflections under various loads for beam C1

Load in kN	Numerical (FEM) deflection in mm	Experimental deflection in mm
0	0.0000	0.0000
2	0.0175	0.0220
4	0.0349	0.0400
6	0.0530	0.0580
8	0.0699	0.0780
10	0.0873	0.0940
12	0.1048	0.1120
14	0.1223	0.1280
16	0.1398	0.1460
18	0.1573	0.1620

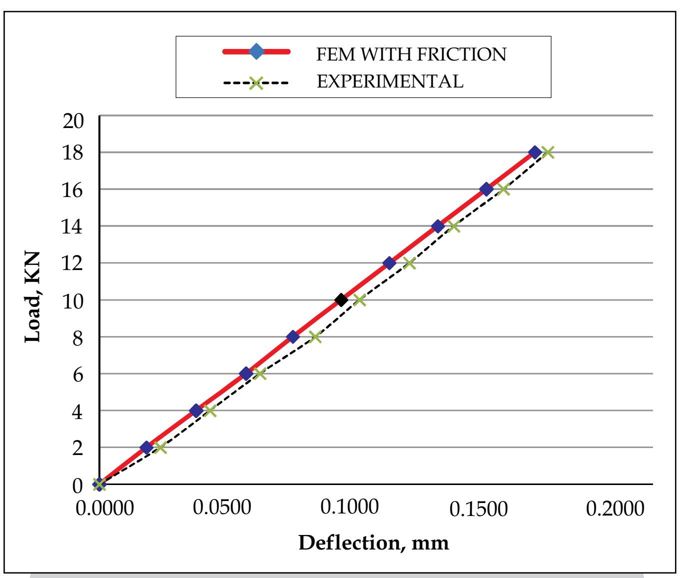

Figure 12. Load v/s deflection for beam C1

Table 6. Deflections under various loads for beam A2

Load in kN	Numerical (FEM) deflection in mm	Experimental deflection in mm
0	0.0000	0.0000
2	0.0170	0.0220
4	0.0350	0.0400
6	0.0524	0.0580
8	0.0699	0.0780
10	0.0874	0.0940
12	0.1049	0.1120
14	0.1224	0.1280
16	0.1398	0.1460
18	0.1573	0.1620
20	0.1748	0.1820
22	0.1923	0.2000
24	0.2098	0.2180

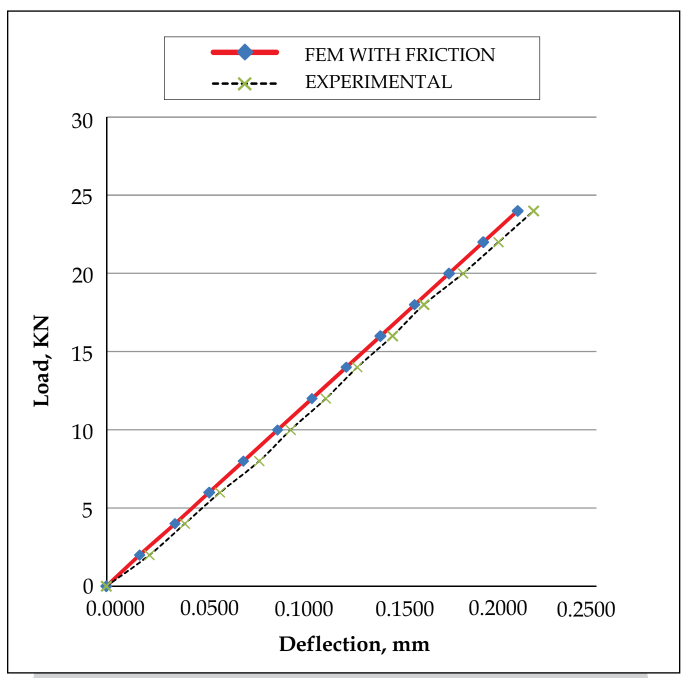

Figure 13. Load v/s deflection for beam A2

Testing of PSC beam B2 is done on applying prestressing force of 44.96 kN, for different loads and corresponding deflections obtained. The load deflection data considering total prestressing loss using FEM and experiment is given in Table 7 and plot is given in Figure 14. Again, it can be observed that both the results are quite close to each other. The friction loss, anchor slip loss and total losses are calculated and given in Table 2.

Table 7. Deflections under various loads for beam B2

Load in kN	Numerical (FEM) deflection in mm	Experimental deflection in mm
0	0.0000	0.0000
2	0.0180	0.0220
4	0.0350	0.0380
6	0.0530	0.0580
8	0.0700	0.0800
10	0.0875	0.0920
12	0.1049	0.1120
14	0.1224	0.1260
16	0.1399	0.1440
18	0.1574	0.1620
20	0.1749	0.1820
22	0.1923	0.1960
24	0.2098	0.2120

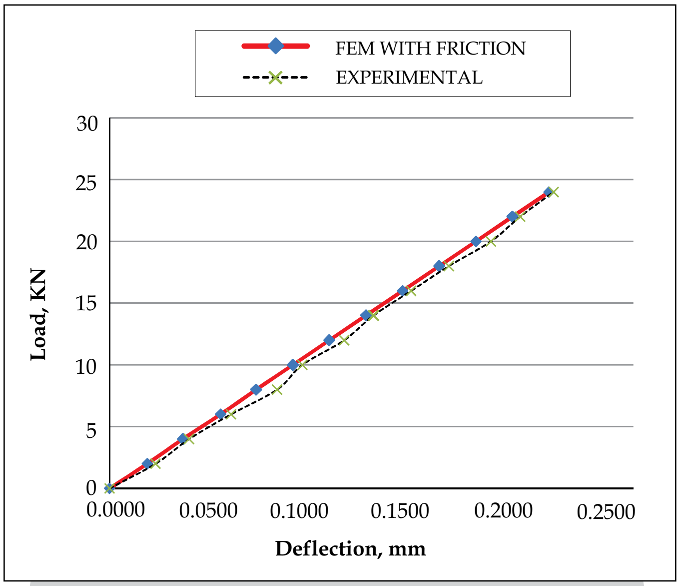

Figure 14. Load v/s deflection for beam B2

Testing of PSC beam C2 is done on applying prestressing force of 51.36 kN, for different loads and corresponding deflections obtained. The load deflection data considering total prestressing loss using FEM and experiment is given in Table 8 and plot is given in Figure 15. Again, it can be observed that both the results are quite close to each other. The friction loss, anchor slip loss and total losses are calculated and given in Table 2.

Table 8. Deflections under various loads for beam C2

Load in kN	Numerical (FEM) deflection in mm	Experimental deflection in mm
0	0.0000	0.0000
2	0.0180	0.0220
4	0.0350	0.0380
6	0.0530	0.0580
8	0.0700	0.0800
10	0.0877	0.0920
12	0.1052	0.1120
14	0.1227	0.1260
16	0.1401	0.1440
18	0.1576	0.1620
20	0.1751	0.1820
22	0.1926	0.1960
24	0.2101	0.2120
26	0.2275	0.2280

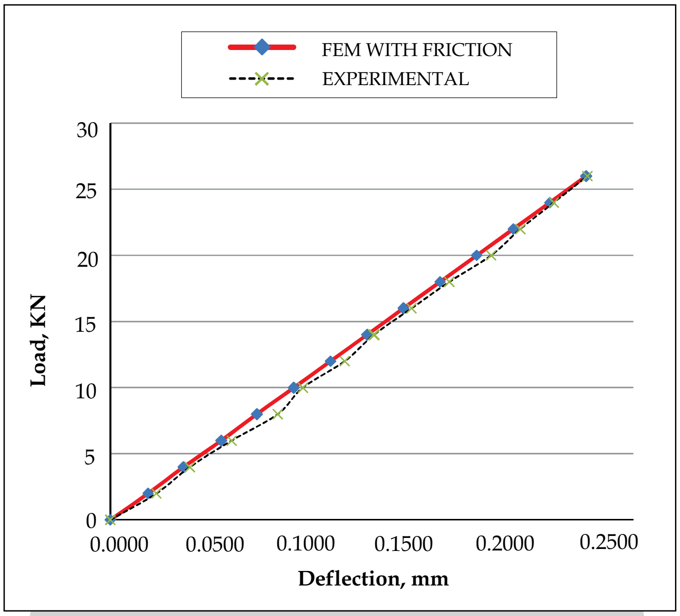

Figure 15. Load v/s deflection for beam C2

6. CONCLUSIONS

The experimental and numerical investigations of PSC beams are compared in this study. For experiment, PSC beams are cast in laboratory. The beam models were loaded for different loads, while deflections on the external concrete surface were monitored. Finite element analyses were performed by using an in house developed code. The nine node elements were used to model the concrete, prestressing tendon was modeled by using 3 node bar element. Using the deflections obtained from experiment, FEM and analytical approaches, a methodology has been developed to calculate friction and anchorage losses. For effective utilisation of prestress, it is concluded that anchorage loss should be given proper attention as it may vary considerably. Friction loss is found to be constant for a particular type of beam.

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