PRESTRESSED CONCRETE BEAMS UNDER FATIGUE LOADING

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ABSTRACT

Fatigue is a critical effect to consider in the design and evaluation of composite bridges such as RCC deck slab over prestressed concrete (PSC) girders. Fatigue may also endanger the durability of PSC bridges mainly due to fatigue in rebars and prestressing strands. For most PSC highway bridges with short and medium span, traffic is the most important action leading to fatigue. Most bridges in major cities experience large traffic volume. For assessing the service life of prestressed concrete (PSC) bridges, the component of a bridge such as beams/girders are subjected to repeated loads transferred from the deck slab that normally covers live loads due to moving vehicles. The number of load cycles may be as low as a few hundreds cycles or as high as several million cycles. Fatigue failure can also occur in PSC structures in addition with other causes of deterioration. Very little research, however, has been done on experimental work of PSC structures under fatigue loading. The present research work deals with the simulation of traffic live load on beam element and beams are subjected to cyclic loading. The experimental work has been carried out on the beams of 3.4 m span under simulated live load till the crack appears. The beams have been tested for ultimate collapse load also. The experimental results of fatigue tests on bonded and unbonded beams shows the development of flexural cracks along the depth & near to mid span portion of the beam under designed live load which provides information about the service span of a bridge under extreme loading case.

INTRODUCTION

A prestressed concrete structure has many advantages, such as delaying cracks, saving materials, reducing deflection, and has been widely or increasingly used in long-span structures [Lin and Burns (1982)]. In order to analyze these sophisticated and complex prestressed concrete structures accurately and efficiently, several nonlinear models for prestressed concrete structures have been proposed during the past decades [Nikolic and Mihanovic (1997)].

For bonded tendons, the deformation field of the tendon is the same as that of the concrete on the interface. Therefore, the analysis from prestress transfer to whole loading history, including relaxation of prestress, shrinkage and creep of concrete, can be carried on directly with the combined stiffness of concrete, steel, and tendon. However, in the case of unbonded tendons, including bonded post-tensioned structures in the prestressing transfer stage, the deformation field of the tendon is not equal to that of concrete, except at the anchorages. In order to represent the interaction between the concrete and tendon, the contribution of the tendon is represented by equivalent nodal loads. In order to satisfy the displacement compatibility between concrete and tendon at the anchorage, complex iterative procedures are needed due to the interactions between concrete and tendons, and among multiple tendons.

Internal unbonded tendons are used widely in prestressing concrete structures. Flexural deformation of an unbonded prestressed member subjected to load, leads to an increase in the stress level in the tendon. In a simply supported unbonded prestressed concrete beam, subjected to a concentrated load at mid span, the strain induced in the concrete at the level of the tendon due to this load, varies according to the bending moment diagram [Allouche (1996)]. Compatibility of deformation requires that the tendon elongate by an amount equal to the deformation in the concrete over the length of the tendon, resulting in an increase in the strain in the tendon. The strain increment, and accompanying stress increment, will be uniform over the length of the tendon, assuming that no friction exists between the tendon and its duct.

Determination of this stress increment is necessary to calculate the moment of resistance of a cross section in an unbonded member. The analytical and experimental studies have been conducted by Allouche,(1996) to identify factors that influence this stress increment such as concrete compressive strength, amount of prestressed reinforcement, and the span to depth ratio.

The existing body of knowledge on the behavior of continuous beams and slabs, prestressed with unbonded tendons, is limited, with the result that the effects of parameters such as pattern of loading and amount of compression reinforcement at the support are not considered in the code equations.

Olson et al (1990), carried out experimental study of 4 PSC bridge girders after 20 years in service and examined the performance of girders which were originally designed under various fatigue loading levels (with no tension, allow tension up to $0.25\sqrt{f_{ck}}$ MPa and $0.50\sqrt{f_{ck}}$ MPa respectively). The girders were subjected to fatigue loading of various number of load cycles at different loading levels and plotted the load deflection curves at the end of each fatigue loadings. The loading begun with 0.5 Million cycles of decompression (that is , with no tension). After satisfactory performance through this loading history, stress ranges were collected and the fatigue loading level was increased to $0.25\sqrt{f_{ck}}$ MPa nominal tension. Once again the specimen survived 0.5 Million cycles of loading. Stress ranges were collected and the loading increased to $0.50\sqrt{f_{ck}}$ MPa nominal tension. After 0.282 Million cycles of loading, at this level a strand failed. The fatigue loading was stopped and the specimen was tested statically to failure.

OBJECTIVES OF PRESENT INVESTIGATION

The main objective of the present investigation is to study the development of cracking, ultimate moment carrying capacity and load-deflection response of post-tensioned bonded & unbonded beams in flexure. Except under special circumstances, unbonded prestressed structures are not preferred generally, mainly because the steel is exposed in some structures and hence likely to be corroded. In other structures, even if the steel is inside the concrete it might still get corroded wherever micro-cracking occurs. The micro-cracks may be due to the shrinkage of concrete, occurrence of temperature gradient from surface to the inside of the structure when the concrete is hardening and due to exposure to an aggressive atmosphere to obtain bonded behavior through grouting.

DESIGN OF PRESTRESSED BEAM AND SUIMULATION OF LIVE LOAD:

The simply supported PSC beams are 3.4 m long, spanning 3.0 m between the centers of supports as shown in Fig.1 (a). The beam had rectangular cross section having size 15cm x 30 cm, Fig.1 (b). The beam is designed for its dead load, super imposed dead load and simulated live load. The two point load on each 1/3rd span is evaluated by calculating the equivalent bending moment due to simulated live load. The MS frame of I section is designed to transfer single vertical load from actuator to two point load at the required location.

Material Properties

Prestressing steel

Select 7 ply 12.7 mm nominal diameter of strand (Low relaxation class II strand, confirming to IS 14268:1995).The properties of 7 ply 12.7 mm diameter strand are as follows:

a) Nominal area = 98.7 mm^2

b) Ultimate tensile strength = 1860 MPa

c) Breaking Strength of Strand = 183.7 KN

d) Allowable prestressing force in strand cables at stressing end before Seating of anchorages (as per clause 8 of IRC: 18-2000) = 0.9*0.85*183.7 = 140 KN

e) Allowable tensile strength = 0.9*0.85*1860 = 1423 MPa

Grade of concrete

Mix of concrete for prestressed beam is taken M 45.

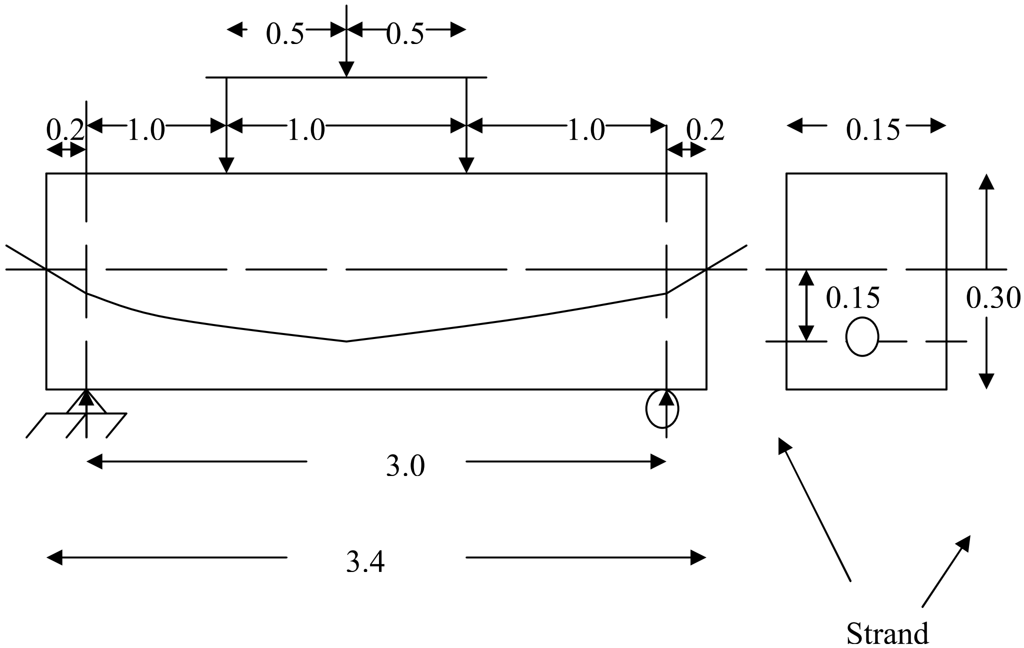

Fig. 1(a) Longitudinal Section of beam **Fig. 1(b) Cross Section of beam**

Simulation of Live Load

Details of IRC live loadings

As per Appendix I of clause 207.1.1 of IRC:6-2000, select load class as 5R wheeled vehicle, four wheeler(Fig. 2). The maximum axle load is 2.2 ton . The equivalent two point load on 3.4 m span test beam is evaluated to simulate the maximum bending moment obtained from the Influence line diagram from Fig. 2.

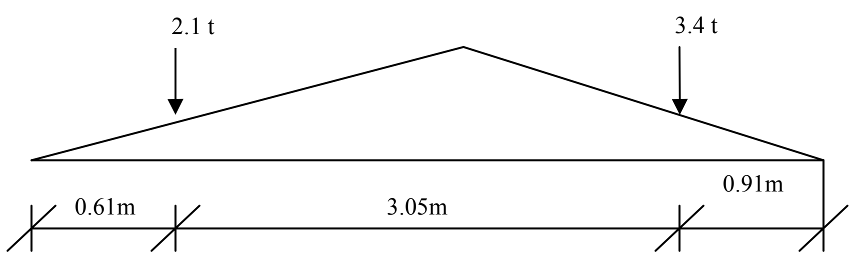

Fig. 2 B.M. Influence line diagram at mid span due to Class 5R loading

The beam is checked for initial stage of prestressing, at service load condition, ultimate load stage as per the IRC codal provisons with the adequate consideration of prestress loss during the period between prestressing and testing of the beams. The proper parabolic profile lay out of strand was formed and placed the non-prestressed skeleton reinforcement including main and shear steel. The beams are casted in the lab and compaction of concrete was carried out be needle vibrator. Proper quality control was carried out such as cube test, slump test etc.

EXPERIMENTAL PROGRAMME:

The sequence of experimental work carried out in the lab is shown in Table 1.

Table 1: Sequence of Casting, Prestressing, Grouting and Loading Operations

S. No.	Days from concreting of girder	Operation
1.	1st day	Casting: Cast the beam.
2.	21st day	Prestressing: Stress one end of strand upto allowable stressing force of 140 KN while locking other end with barrel and wedge, then locked the prestressing end also.
3.	22nd day	Check the anchorage and groute the prestressing strand.
4.	29th day	Apply live load cyclically till appearance of small cracks and then test for ultimate load.

Prestressing Operation

The prestressing operation was carried out by trained and qualified person of field technician of M/S Usha Martin, New Delhi as per the Appendix-4 of IRC: 18-2000. The prestressing strand is as per IS 14268:1995(Select 7 ply 12.7 mm nominal diameter of strand, Low relaxation class II strand). The Single strand jack (J-20) and other accessories was of authorized manufacturer, M/S Usha Martin, New Delhi. The prestressing force of 14 ton is gradually applied with increasing gauge pressure (0 to 335 Kgf/cm^2) in three phases as per the manufacturer's requirement of single stand hydraulic jack.

The ram area of ingle-pull jack = 42.2 cm$^{2.}$ Jack pressure = prestrssing force /ram area = 14,000 kgf /42.2 cm^2 = 332 kgf/cm^2. Table 2 shows the pressure applied to tendon systematically and noted the elongation of strand.

Table 2: Extension of Strand with the Increase of Jack Pressure for Beam No. 1

Sr.No.	Gauge pressure in single strand Jack (kgf/cm^2)	Jack reading	Extension of strand (mm) by increase of pressure	Total Extension of strand (mm)
1.	0	75	0	0
2.	50	80	5	5
3.	100	85	5	10
4.	150	90	5	15
5.	200	95	5	20
6.	250	101	6	26
7.	300	105	4	30
8.	310	106	1	31
9.	320	107	1	32
10.	330	108	1	33
11.	332	109	1	34

The PSC beams were raised (lift) by 2 mm at the centre after completing the prestressing operation. Jack reading at the application of full prestressing force = 109 mm.

Jack reading after unloading the jack pressure = 97 mm.

So, the slip = 109 – 97 = 12 mm.

Elongation = Total extension of the strand – slip = 34-12 = 22 mm.

Elongation = allowable tensile stress *L/ E_s =1423 MPa * 3000 mm /$1.95x10^5$MPa = 22 mm

Photo 1 shows the prestresing operation carried out in the lab.

Grouting Operation

The grouting of beam (bonded case) was carried out as per the guidelines of IRC: 18-2000. The detailed of grouting specification, materials used and methodology are given in Appendix 5 of IRC: 18-2000. Photo 2 shows the grouting operation in progress.

Photo 1: Prestresing Operation in Progress **Photo 2: Grouting Operation in Progress**

Testing of Beams under Fatigue and Ultimate Loading

The testing operation is focused on assessing the fatigue performance and ultimate strength response of PSC beams. The results from the experimental testing program described herein are compared with that calculated by the equation in the IRC: 18-2000.

Fatigue testing of beams

The bonded and unbonded beams are subjected to 2.2 ton cyclic loading of sinusoidal wave (Fig. 3) at centre of beam by single hydraulic actuator in such a way that I section placed on top of beam distribute the load at two point load at each $1/3^{rd}$ span from the ends (Photo 3). The actuator operating at 5.56 cycles per second. Fig.3 shows the pattern of applied actual cyclic loading (shown only up to 200 sec only) by the hydraulic actuator in the lab. After appearance of fine cracks and propagation or widening of the cracks (Photo 4), the test has been carried out for ultimate load.

Ultimate load test of beams

After appearance of flexure cracks near the mid span, the beam is subjected to linear static loading at the rate of loading of 0.1 kN/sec. Photo 5 shows the collapse of the beam at ultimate load of 110 kN. The real data obtained from the fatigue testing machine are plotted and Fig. 4 shows the mid span deflection (mm) with linearly increasing applied vertical load (kN). It is observed from this graph that the ultimate collapse load of the beam is 110 kN and maximum mid span deflection is 37 mm.

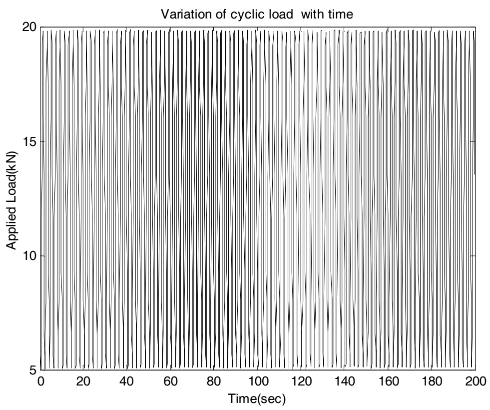

Fig. 3 Sinusoidal wave of 5.56 Hz

Photo 3: A view of the PSC beam for testing

DISCUSSION

The post-tensioned prestressed bonded beams were tested along with unbonded beams for fatigue & ultimate loading stage and the experimental results are presented in this thesis. The beams are rectangular in cross-section of size 15cmx30 cm, simply supported and loaded two pointy loads at one third span point from the ends. Development of cracking pattern, behavior beyond the service loads and load deflection response are studied. The results of the ultimate/collapse load test are compared with those computed with IRC codal guidelines.

Photo 4 Appearance & Propagation of Crack in the Beam During Fatigue Loading

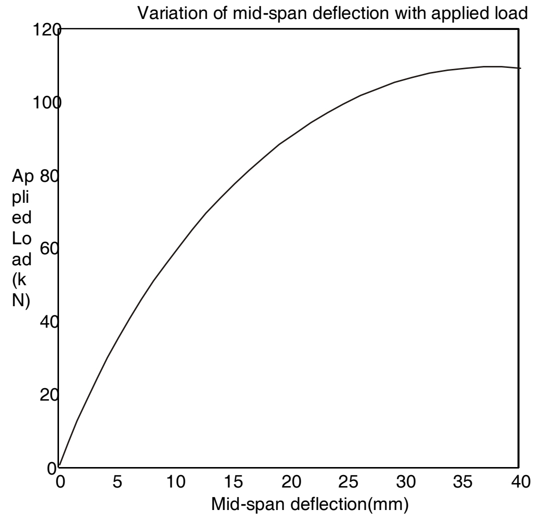

Photo 5 A View of Beam in Ultimate Stage

Fig. 4 Variation of Deflection with Load

SUMMARY

The beams of 3.4 m span are designed for dead load, superimposed load and service live load simulated by class 5R loading as per IRC-18:2000. The casting, prestressing and grouting operations were performed on the beams. The quality control of the material such as cement, sand, the aggregates, mix designed, prestressing strand, grouting of cement slurry etc, was carried out by various lab test and confirmed as per the required standard. The Fatigue and Ultimate load test on the beams are carried out to study the fatigue performance and ultimate collapse stage of PSC beams.

RESULTS

The test results of all the bonded and unbonded beams subjected to fatigue and ultimate load tests are presented in Table 3. The comparative studies for bonded and unbonded beams are carried out under cyclic loading and ultimate loading. The ultimate load of the psc beam is valuated as per IRC 18-2000 and these predicted results are compared with the experimental results.

Table 3: Comparison of Test Results of Bonded and Unbonded Prestressed Beams

S. No.	Beam Type	Average crushing strength	Nos. of cycles at which first crack appear	Ultimate static load as per lab test	Ultimate load as per IRC 18-2000	Deflection at the center of the beam at first crack	Deflection at the center of the beam at ultimate load
1.	Beam no.1 Bonded	51.0 MPa	0.5 Million	110 kN	61 kN	1.00 mm	37 mm
2.	Beam no.2 Unbonded	52.0 MPa	0.45 Million	83 kN	61 kN	1.25 mm	33 mm

CONCLUSIONS

The deflection pattern for the bonded and unbonded prestressed beams tested proves the validity of theory that is defined as a maximum deflection of prestressed concrete bridges upto the functionality limit is equal to span length/100.

- It is observed from the ultimate load test on the beams that the IRC code under stimates the ultimate load of the psc bemas.
- The experimental results of fatigue tests on bonded and unbonded beams shows the development of flexural cracks along the depth & near to mid span portion of the beam under designed live load after a number of million cycles which provides information about the service span of a bridge under extreme loading case.

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