An Experimental Study of residual strain in partially prestressed concrete beams under fatigue loading

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Summary

This paper gives details of a fatigue test programme of partially prestressed concrete T-beams. A total of six beam specimens were tested under various fatigue load ranges until failure. In addition, two specimens were tested for monotonic capacity. The residual strains of the compressive concrete and the tensile reinforcement steel were measured by FBG sensors and strain gauges at different numbers of load cycles during the tests. Based on the experimental results, the propagation process of residual strains in the non-prestressed steel reinforcement was presented, and an empirical formulas between residual strains and the cyclic number were developed. In addition, a theoretical method was proposed to quantify the residual strains of the non-prestressed steel reinforcement in partially prestressed concrete beams under fatigue loading. The results show that the theoretical method is in good agreement with the experimental data.

Keywords: Partially prestressed concrete beam; Non-prestressed steel reinforcement; Residual strain; Fatigue loading; Analytical modeling.

Partially prestressed concrete structures are increasing being used in long span bridges. Fatigue may be a concern in these structures, owing to the existence of initial flexural cracks that fluctuate with the application of the maximum cyclic loads. Therefore, with regard to the fatigue behavior, many studies have been conducted on the partially prestressed concrete beams. In these studies, some have shown the fatigue loading induces residual strains of the tensile steel reinforcement in beams. The residual strains are those strains that remain in steel reinforcement after eliminating the application of the external loads when cycle numbers amount to a certain value. It is worth noting that these residual strains may add to steel stress levels in beams and lead to premature fatigue failure of the partially prestressed concrete beams at lower loads than might be expected. Generally speaking, fatigue resistance of partially prestressed beams is typically investigated by calculating the stress range produced in the non-prestressed steel reinforcement during fatigue loading and comparing this stress range with that obtained from S-N curves for the non-prestressing steel reinforcement. This shows an accurate prediction of the stress in the non-prestressed steel reinforcement is very important for the fatigue design of partially prestressed concrete beams. However, to date, little attention has been paid to the effect of the residual strain of the non-prestressed steel reinforcement on steel stresses in beams under fatigue loading. Hence it is evident that more research is needed on the residual strain of non-prestresesed steel reinforcement in partially prestressed concrete beams under fatigue loading.

This paper presents a fatigue experimental study of post-tensioned partially prestressed concrete beams in which the residual strains of concrete and the tensile steel reinforcement were monitored

https://doi.org/10.2749/222137813815776179
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using FBG sensors during the constant-amplitude fatigue loading until failure. The primary objectives of the research are to study the evolution of residual strain of non-prestressd steel reinforcement in partially prestressed concrete beams during the fatigue loading and propose a model approach to predict the residual strain of non-prestressd steel reinforcement in partially prestressed concrete beams.

Some of reasons for the residual strain in the non-prestressed steel reinforcement can be briefly stated: (1) In order to maintain strain compatibility with the residual strain in the concrete compression region, producing the residual strain in the non-prestressed steel reinforcement.(2) Microcracking will take place in the weak areas of concrete around the reinforcing steel when the non-prestressed steel reinforcement subject to tension stress, due to the bond reaction between the concrete and the deformed bars. On the other hand, the application of cyclic loading typically leads to increasing residual slip with increasing number of cycles. Then the microcracking in concrete can not close down completely and the reversed frictional resistance of the reinforcing steel is formed in the process of unloading, which induce residual stress (strain) in the non-prestressed steel reinforcement.

Three distinctive stages of the residual strain evolution in non-prestressed steel reinforcement observed in fatigue test for beams. In the first phase ($0<n/N_f\leq 0.1$), residual strains increase rapidly; in the second phase ($0.1< n/N_f < 0.8$), residual strains increase slowly and steadily; in the third phase ($0.8\leq n/N_f <1$), residual strains increase rapidly.

The evolution of residual strain of non-prestressed steel reinforcement in beams was obtained through a non-linear analysis of the fatigue test results and the mathematical relationship is given in the following.

$$\varepsilon_{sr,n}=768.81\,(n/N_f)^3- 1039.4\,(n/N_f)^2+ 463.16\,(n/N_f) + 172.87 \quad (R=0.867) \quad (1)$$

Where $\varepsilon_{sr,n}$ is residual strain of non-prestressed steel reinforcement in beam, n/N_f is the cycle ratio of beam.

The calculation model of residual strain in non-prestressed steel reinforcement in beams under fatigue loading is expressed as:

$$\varepsilon_{sr,n} = \frac{\gamma \cdot f_{ct,n}}{2E_{cn}} \quad (2)$$

$$r = \frac{A_s}{2A_s^f} + \sqrt{(\frac{A_s}{2A_s^f})^2 + \frac{2\pi d_s E_{cn} W_{sr,n}}{n_f \beta_n f_{ct,n} A_s^f}} \quad (3)$$

Where A_s is the initial area of the non-prestressed steel reinforcement; A_s^f is the effective area of non-prestressed steel reinforcement; E_{cn} is the cycle dependent secant modulus for concrete at any number of cycles. $n_f = E_s/E_{cn}$, E_s is the modulus of elasticity for non-prestressed steel reinforcement, d_s is the diameter of steel reinforcement; $f_{ct,n}$ is the fatigue tensile strength of concrete; β_n=1, $W_{sr,n}$ =0.02

After Eq.(3) is solved for r and substituted in Eq.(2), the residual strain in the non-prestressed steel reinforcement (ε_{sr}) can be evaluated. A good agreement exists between the values obtained from the model and those measured. Therefore, it indicates that the proposed analytical models can predict the residual strain of the non-prestressed steel reinforcement in beams.