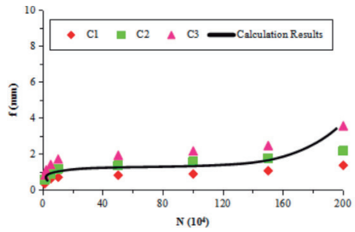
Deflection calculation of partially prestressed concrete beams under heavy duty



Cálculo de la flecha de vigas de hormigón parcialmente pretensadas para trabajos de carga intensa

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RESUMEN

- Para predecir las leyes de deformación de un puente bajo cargas de tráfico e identificar los principales factores que influyen en el desplazamiento máximo de la estructura, este estudio llevó a cabo pruebas estáticas y de fatiga en siete muestras de vigas a escala de hormigón pretensado, utilizando el método de pre-tensionado. Se aplicó el método de cálculo de la flecha en vigas de hormigón parcialmente pretensadas bajo cargas severas. Los resultados muestran que las variaciones de las tensiones en el hormigón a lo largo del canto de la sección se ajustan a la hipótesis de que la sección permanece plana tras la deformación. La flexión de vigas de hormigón pretensado bajo cargas severas se ajusta básicamente a la ley de variación "rápido-estable-rápido", y la tasa de variación es significativamente más alta que con cargas operativas normales. El desplazamiento tras el agrietamiento por fatiga en vigas de hormigón pretensado bajo cargas severas, puede calcularse a partir de las flexiones residuales y las debidas a la carga. Basado en la fórmula establecida para el ajuste de la flecha, el coeficiente de flecha de un estado de fatiga estable es aproximadamente del 20%-35%, y el coeficiente para fallo crítico es aproximadamente del 80%-100%. Este estudio proporciona referencias para la evaluación del comportamiento a fatiga de vigas de hormigón pretensado bajo grandes cargas de tráfico y la selección del tipo de refuerzo.
- **Palabras clave:** Cargas severas, Ensayo de fatiga, Vigas de hormigón parcialmente pretensadas, Cálculo de la flecha.

ABSTRACT

To predict bridge deformation laws under existing traffic loads and identifies the main influencing factors of midspan deflection of the structure, this study performed static and fatigue tests on seven pieces of prestressed concrete scale model beams using the pre-tensioning method. The general variation laws and characteristics of deflection were studied, and the calculation method of deflection of partially prestressed concrete beams under heavy loads was discussed. Results demonstrate that the changes of concrete strain along the section height conform to the plane hypothesis. The deflection of prestressed concrete beams under heavy load basically conforms to the "quick-stable-quick" variation law, and the change rate is significantly higher than that under normal operating loads. The deflection after the fatigue cracking of prestressed concrete beams under heavy load can be calculated from the residual and load deflections. Based on the established formula of fitting deflection, the amplification coefficient of deflection during the fatigue steady state is approximately 20%–35%, and the amplification coefficient at critical failure is approximately 80%–100%. This study provides references for the fatigue performance assessment of prestressed concrete beams under heavy traffic loads and the selection of reinforcement time.

Keywords: Heavy duty, Fatigue test, Partially prestressed concrete beams, Deflection calculation.

1. INTRODUCTION

Partially prestressed concrete structures have been widely used in crane beams, highway and railway bridges, and other structures[1-3]. During their service period, while under the effect of static load, they are also subjected to frequent repeated loading[4, 5]. Their resistance decays with the accumulation of fatigue damage, eventually leading to structural deterioration or failure. For example, the deformation of partially prestressed concrete beams under fatigue load gradually increases, while their excessive deformation may affect the normal serviceability and even the safety of structures. Therefore, the component deformation and section stiffness of partially prestressed concrete beams under fatigue load should be studied.

Existing experimental analyses on fatigue damage mechanisms have mainly focused on reinforced concrete beams under non-overloaded conditions [6, 7]. However, total vehicle and axial loads frequently exceed the design load of a highway bridge during actual service [8-10]. Heavy duty refers to the drastic deterioration of pavement performance under high traffic volume or under cumulative equivalent standard axle that exceeds the general level; heavy duty is mainly manifested as vehicle overload [11]. Overload indicates that a highway bridge is loaded with vehicles beyond its maximum carrying capacity [12]. Each pass of a vehicle over a bridge is equal to one loading and unloading cycle. Cyclic loading easily causes various damages to bridge structures. A survey on vehicle overload behaviors revealed that the service life of highways, which are designed to serve for approximately 15 years, will be shortened to 1 year if all vehicles carry loads that twice that of their maximum carrying capacity. Worldwide, many highway bridges, which were constructed with large amounts of funds, exhibit subsidence, hollow spots, tracking, bridge pavement damage, and plate rupture during their first and two years of service. Defects that are caused by vehicle overload will significantly affect the safety and reliability of existing bridge structures and incur high repair costs [13, 14]. Hence, the effective maintenance of highway bridge structures, accurate prediction of the fatigue service life of bridges, and elucidation of the bridge failure mechanism caused by vehicle overload are issues that require urgent resolution.

Based on the above analysis, seven pieces of prestressed concrete beams, which were prepared by the pre-tensioning method, were used as research objects in this experiment. An overloading condition was designed based on the collected traffic flow data. A fatigue test of these prestressed concrete beams under heavy loads was conducted to discuss the deformation of members and the rigidity of the section.

2. STATE OF THE ART

Many studies have investigated bridge structural damages caused by heavy duty. Walter considered the effects of heavy duty and overload limit, as well as established the definitions of these two variables [15]. Ayilara analyzed the impact of the overloading on the steel bridge [16]. Nevertheless, their study only included qualitative interpretations without quantitative analyses. Zhou et al. established a universal simulation platform by using a numerical analysis system. To predict the global dynamic response of bridges under load, the universal simulation platform was used to develop a bridge traffic model under completely coupled combined and ultimate loads [17]. The BEASTA, a system was unveiled by Rutgers University to simulate decades of bridge deterioration in a matter of months [18]. Nonetheless, the fatigue damage mechanism of the bridge structure was not discussed. Han et al. developed advanced analytical software for bridge interaction and numerically explored the dynamic responses of a highway bridge with medium span under selected traffic conditions. The feasibility of the developed system for predicting the dynamic responses of the bridge structure under normal load was verified by its results with existing provision [19]. Saiedi et al. observed the behavior of precast concrete beams prestressed using carbon fiber-reinforced polymer rods that under the combined effects of sustained load [20]. However, their study is inapplicable to overload conditions. A health monitoring system on highway bridges was installed by Han et al. in service to enable the statistical analysis of extra-heavy duty sample data and consequently obtained the characteristics of parameters. To analyze ultralimit conditions, a random traffic flow-bridge model by using a computer program coupled with a vibration analysis module was also constructed [21]. Unfortunately, the stress behaviors of bridge structures under ultralimit service conditions weren't explored. Zhang et al. used a group of hydraulic jacks to simulate vehicle overloads of 196 and 294 kN under one lane and dual lane loading, respectively. Their predicted global dynamic responses of bridge under load demonstrated that the measured loading capacity of the test bridge was considerably higher than the design capacity, whereas the measured transverse coupling stiffness of bridges changed slightly from the designed transverse coupling stiffness [22]. Although hydraulic jacks could be used for the accurate application of a preset load on a bridge, the loading method disagreed with the actual stress mode of bridge structures and couldn't reflect the cyclic characteristics of vehicle load. Oudah, Patil, Boone and Zawam et al. developed the damage accumulation of reinforced concrete beams caused by different prestress levels under fatigue load and found that damage accumulation was unrelated to prestress level [23-26]. The impacts of concrete density and strength on the stressed of prestressed concrete members were discussed by Mossakowski and Alberto et al. [27, 28]. However, their study emphasized the prestress degree of the material and the parameter of concrete, but discussed less the influence law of the load-induced deterioration of bridge performance. Therefore, the direct relationship between the fatigue load and deflection changes and the rigidity degeneration of reinforced concrete beams is difficult to disclose.

That is, existing studies focus on the characteristics of heavy-duty traffic and the dynamic response analysis of reinforced concrete beams under specific loads. The degeneration of fatigue performance under different overload amplitude, especially the

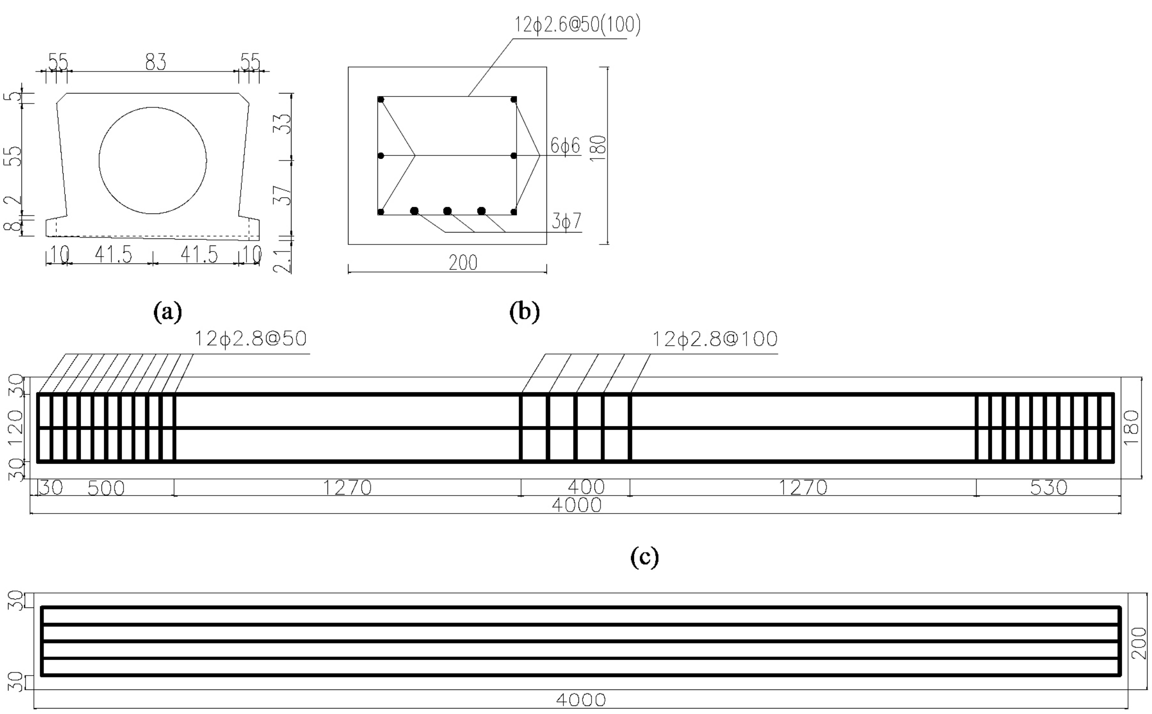


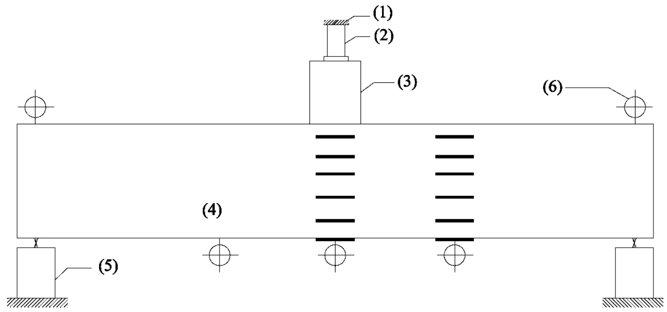
Fig. 1. Structure diagram of the beam structure. (a) Cross-sectional dimensions of the prototype hollow beam (16 m). (b) Model beam cross section. (c) Elevation schematic. (d) Floorplan

quantitative analysis of the deformation of prestressed concrete members under overloads, has received minimal attention. Based on the characteristics of heavy-duty traffic, loads with different overload amplitude were used as variables in this study to discuss the deformation laws of beams under different load limits. The relationship between load circulation ratio and deflection changes of beam was established.

The remainder of this study is organized as follows. The static and fatigue tests based on a reasonable scale model, as well as the derivation of ultimate bearing capacity and fatigue service life, are discussed in Section 3. An analysis of the crack propagation, load carrying capacity, midspan deflection and calculation formula of deflection based on cyclic ratio is presented in Section 4. The last section summarizes the entire research and provides relevant conclusions.

3. METHODOLOGY

Based on the principle of similitude, seven pieces of partially prestressed concrete of simply supported beams were prepared by the pre-tensioning method and denoted as S1, S2, S3, C1, C2, C3, and C4. The test beam models prepared through pretensioning method on a reduced scale of 1:4. The solid rectangular section of the model beams was , and the calculated length of the beams was 3.7 m. The concrete material of the model was same as that of the original structure. The concrete strength grade was C40, and the thickness of the protective layer was 30 mm. The diameter of the aggregate used in the concrete did not exceed 20 mm. The prestressed steel wires utilized in the prestressed steel bars were , and the tension stress was 0.73 times that of the standard value for tensile strength. The maximum strengthening value did not exceed 1.05 times that of the standard value for tensile strength. HPB300 steel bars with 6 mm diameter were selected as common bars. Iron wire (12#) with 2.6 mm diameters were selected as stirrups. The spacing was 100 mm, and the spacing close to supports was narrowed to 50 mm.The size and reinforcing bar layout of beams are shown in Figure 1.



(1)Reaction beam, (2)Pressure sensor, (3)Hydraulic jacks, (4)Test beam, (5) Support pier, (6)Motion detector

Tests include static and fatigue tests. The static test was conducted with three pieces of test beams to obtain the cracking and ultimate loads of the beam structure. Static test results are shown in Table I.

The experiment used an equal amplitude sine wave loading, and the loading frequency was 2 Hz. In this study, the lower limit of the fatigue load was 0.15 times the value of the ultimate load M_u, and the maximum loads of the constant amplitude fatigue

Fig. 2: Fatigue test and measurement. (a) Measurement. (b)Fatigue test

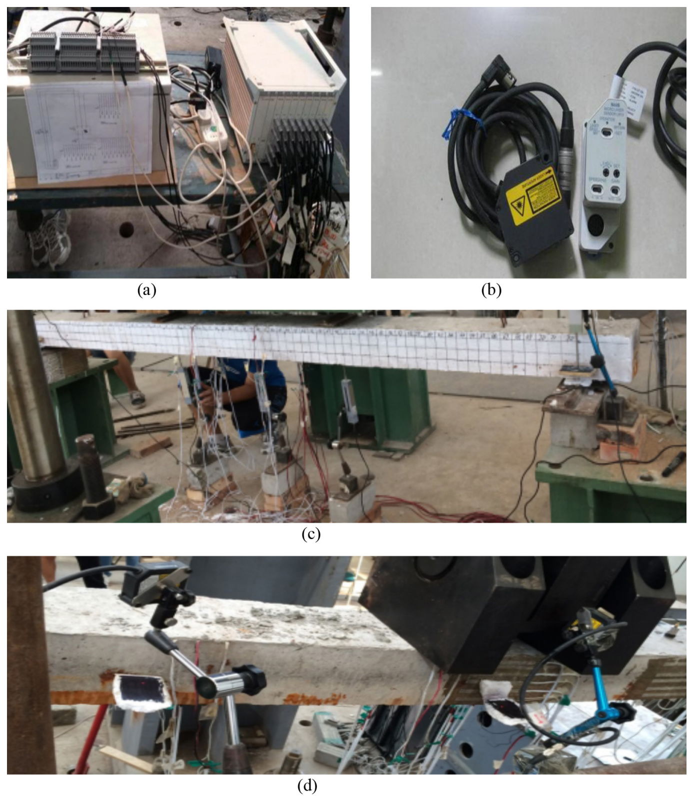


Fig. 3: Measurement system. (a) DH5922 dynamic state signal testing and analyzing system. (b) Laser displacement meter. (c) Static displacement measurement locations. (d) Dynamic displacement measurements

No. of beams	Failure mode	$M_{cr}(kN \cdot m)$		$M_u(kN \cdot m)$	
		Test	Calculation	Test	Calculation
S1	Bending failure	7.41	7.25	24.31	23.60
S2	Bending failure	7.13	7.25	22.91	23.60
S3	Bending failure	7.36	7.25	23.68	23.60
Average value	___	7.30	___	23.63	___

Table I: Static test results

Test	Beam No.	Loading system (kN)			Fatigue life or ultimate strength under static load	Failure mode
		Lower load limit	Upper load limit	Amplitude		
Constant amplitude fatigue test	C1	4	12	8	$N \geq 2000000$ $P_u = 20\ kN$	Undamaged after 2 million cycles of loads and subsequent bending failure under static load
	C2	4	14	10	$N \geq 2000000$ $P_u = 24\ kN$	Undamaged after 2 million cycles of loads and subsequent bending failure under static load
	C3	4	16	12	$N \geq 2000000$ $P_u = 27\ kN$	Undamaged after 2 million cycles of loads and subsequent bending failure under static load
	C4	4	18	14	N = 102000 Brittle damage	Breakage of steel bars in the pure bending section

Table. II: Service life of model beams in fatigue tests

test were 0.5078, 0.5925, 0.6771, and 0.7617M_u. Among them, 0.5078 M_u was used for the normal operating load, while the other three conditions represented heavy traffic. During the test, when the dynamic load cycles reached 10000 (1W), 20,000 (2W), 50,000 (5W), 100,000 (10W), 300,000 (30W), 500,000 (50W), 1 million (100W), 1.5 million (150W), and 2 million (200W) times, the loading was stopped. After unloading, the residual deflection was measured, and static load test, which loaded to the upper limit fatigue load, conducted. The fatigue test used a single point load, and the test device diagram is shown in Figure 2. Displacement meters were placed at the bearing and mid-span of the test beam to measure the deflection. The concrete and steel strain collection layout is shown in Figure 3. The fatigue test results are summarized in Table II.

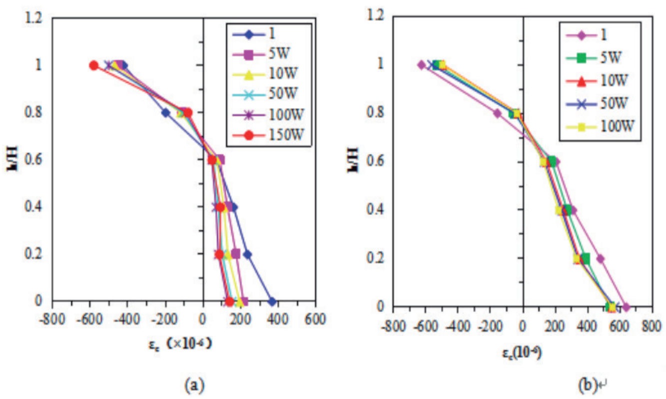


Fig. 4: Vertical strain changes of test beams. (a) C2. (b) C3

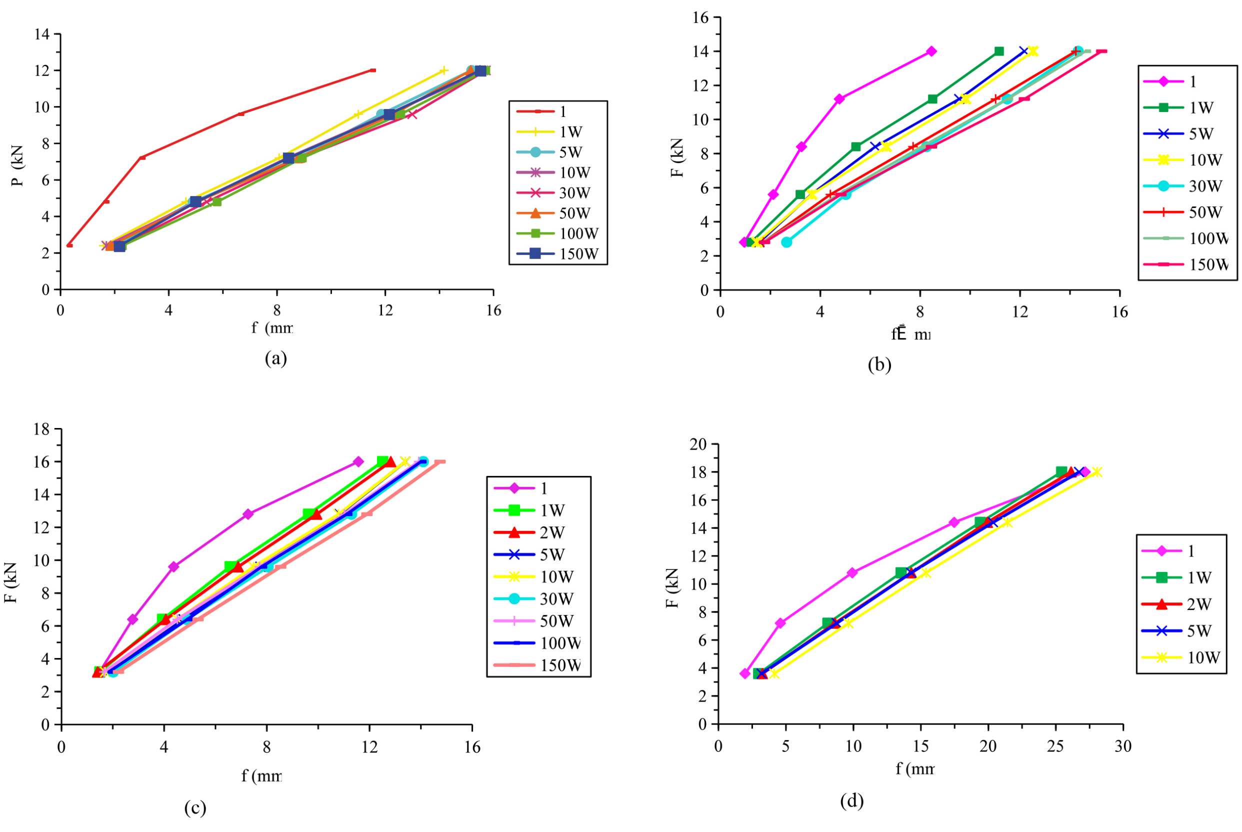


Fig. 5: Load and midspan deflection curves. (a) C1 (b) C2 (c) C3 (d) C4

4. RESULTS ANALYSIS AND DISUSSION

4.1. LOAD AND MIDSPAN DEFLECTION CURVES

The measured strains on the C2 and C3 sections are shown in Figure 4. Before the cracking of concrete in the tensile region (about <300,000 times), the section strain approximately shows a linear change. However, the concretes in the bending tensile region cracked with the increase in application times of fatigue loads. Cracks are developed at the bottom plate of the primary beam, and the neutral axis is shifted up continuously, while the height of the concrete compression zone and the beam rigidity are decreased continuously. The concrete section strain presents a nonlinear growth. Generally, the vertical strain changes of the concrete section under static load after multiple fatigue loads basically conform to the plane hypothesis.

4.2. THE LOAD–DEFLECTION CURVES

The load–deflection curves of the test beams under static and cyclic loads are shown in Figure 5. The growth amplitude of the midspan deflection of test beams is related with fatigue limit and fatigue loading times. Deflection and load basically have a linear relation under all working conditions, except for the first loading. The load–deflection curves are generally developed in the law of "sparse-dense-sparse." This reflects that beam rigidity declines continuously and deflection increases gradually under the fatigue load with the increase of loading times.

The variation curves of the total and residual deflections of test beams with the number of loading cycles (N) are shown in Figure 6. Under fatigue loads, the deflection of beams is positively related with N. For C1-C3, the development of load–deflection

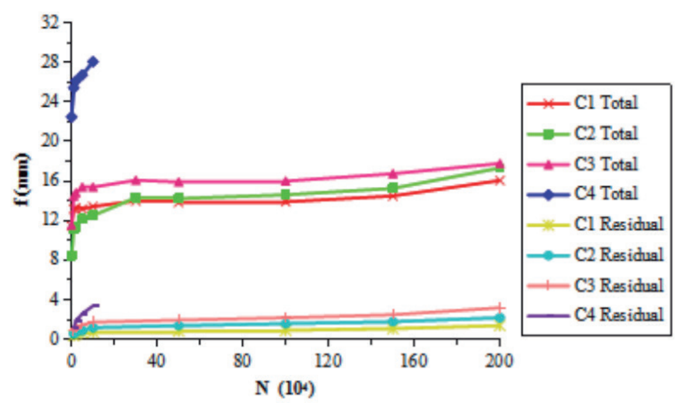


Fig. 6.:Variation curve of midspan deflection with loading cycles

curves can generally be divided into three stages: (1) from the beginning of loading to beam cracking: deflection soars up with the increase of N; (2) from beam cracking to yield: defection becomes stable gradually, showing a stable growth trend; and (3) from yield to ultimate failure: deflection presents an unsteady growth.

The comparison of different deflection growths shows that given the same lower load limit and number of loading cycles, the deflection growth rate and amplitude are positively correlated with the upper load limit. The deflection of beams with an upper fatigue load limit of 0.7617 develops in a straight line in the service period, without a relatively stable stage. Compared to the deflection of C1 after 100,000 of loading times, the deflection growth of C4 is approximately 2.1 times that of C1. This reflects that under overloading, the beam structure is degraded more quickly under more serious overloading, and beam rigidity may drop dramatically in a short time.

Residual deflection increases quickly in the beginning and late periods with the increase of N, but develops slowly in the middle stage. The middle stage is similar with the creeping of concrete [29]. The total deflection growth factor before the failure or at 2 million loading cycles is approximately 1.4 to 1.7.

4.3. DEFLECTION CALCULATION

4.3.1. Residual Deflection

According to the test results, the antiarch of all test beams decreases with the increase of N. This implies the existence of residual deformation. Load deflection increases accordingly. Therefore, the total midspan deflection (f_N) at N of the fatigue loading cycle can be divided into two parts: residual deflection (f_{rN}) and load deflection (f_{1N}).

The variation features of residual deflection were disclosed by the test results. Residual reflection is divided into the residual deflection at the first loading cycle (f_{r1}) and residual deflection under the fatigue loads (f_{rN}-f_{r1}). Based on the calculation method in Reference [30], the formula of f_{r1}, considering the main influencing factors, was established:

$$f_{r1} = a + b\,\frac{M_{max}}{M_{cr}\alpha_E\rho}. \tag{1}$$

According to the regression analysis of test results:

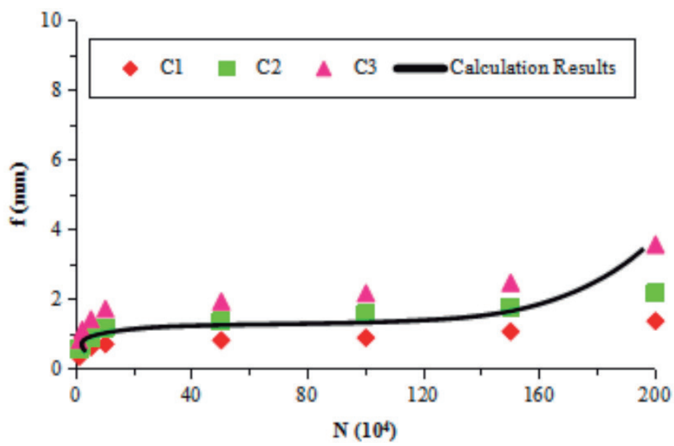


Fig. 7: Comparison between test results and calculated results of residual deflection

$$f_{r1} = -0.06221 + 0.02691 \times \frac{M_{max}}{M_{cr}\ \ _{E}} \tag{2}$$

Where $_E$ =E_s/E_c . =(A_s+A_p)/bh_0 . E_s and E_c are the elasticity modulus of rebars and concrete, respectively. A_s and A_p are the areas of non-prestressed and prestressed rebars, respectively. M_{max} is the bending moment at upper limit of the fatigue loads. M_{cr} is the cracking bending moment.

The variations of residual deflection under fatigue loads (f_{rN}-f_{r1}) basically agree with the "three-stage" development law. The circulation ratio was used as the parameter variable to establish the following fitting formula:

$$f_{rN} - f_{r1} = f_{r1}\left[a + b\left(\frac{n}{N}\right)^d + c\left(\frac{n}{N}\right)^e\right] \tag{3}$$

where n is the number of fatigue loading cycles and N is fatigue life. They are calculated according to the method in Reference [31].Based on the regression test data, the following can be obtained:

$$f_{rN} - f_{r1} = f_{r1}\left[0.4726 + 3.1876\left(\frac{n}{N}\right)^{4.5851} + 3.6781\left(\frac{n}{N}\right)^{5.3997}\right] \quad (4)$$

Hence, the calculation formula of residual deflection is:

$$f_{rN} = -0.6199 + 0.02589\frac{M_{max}}{M_{cr}\alpha_E\rho}\left[1.4726 + 3.1876\left(\frac{n}{N}\right)^{4.5851} + 3.6781\left(\frac{n}{N}\right)^{5.3997}\right] \quad (5)$$

The comparison between the test and calculated results of residual deflection is shown in Figure 7. The calculated results agree well with the test results. In the fatigue steady-state process, residual deflection basically shows a linear steady growth and has a brief period of sharp growth at critical failure.

4.3.2. Calculation methods of load deflection

Under fatigue loads, the calculation methods of load deflection mainly consider the effects of fatigue load by multiplying rigidity with a reduction factor smaller than 1 [30, 31]. This is mainly based on the development characteristics of deflection in the second stage: load deflection becomes stable after a certain

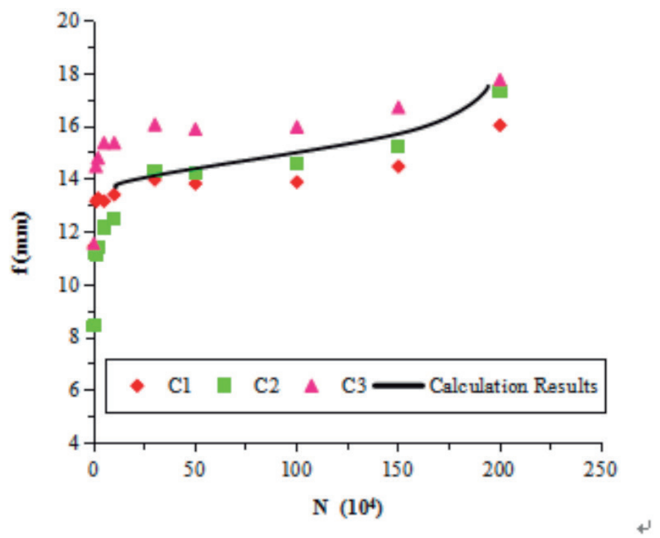


Fig. 8: Comparison between test results and calculated results of load deflection

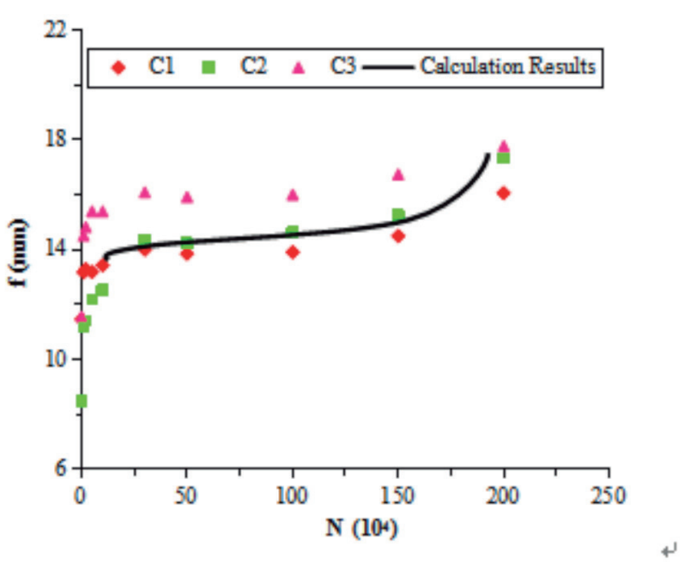


Fig. 9: Comparison between test results and calculated results of total deflection

period of cyclic loads. In this study, the development characteristics of fatigue in all three stages were considered comprehensively. The expression of growth amplitude in n was gained by the statistical method:

$$f_{lN} = f_{l1}\left[a + b\left(\frac{n}{N}\right)^{d} + c\left(\frac{n}{N}\right)^{e}\right] \quad (6)$$

$$f_{lN} = \frac{\alpha M_{max}L^2}{B}\left[1.1798 + 0.65678\left(\frac{n}{N}\right)^{11.13467} + 0.13265\left(\frac{n}{N}\right)^{0.9877}\right] \quad (7)$$

where f_{l1} is the load deflection under the upper limit of fatigue load after 10,000 times. According to the rigidity reduction method, $f_{l1}=\alpha M_{max}L^2/B$ [31] (n is the current number of cycles, B is the bending stiffness and α is deflection factor).

The comparison of the load deflection calculated from Equation (7) and the test results is shown in Figure 8. They agree well. In the fatigue steady-state process, the amplification coefficient of load deflection is approximately 20% to 35%, and the amplification coefficient of load deflection at critical fatigue is 80% to 100%.

4.3.3. Total deflection

According to the superposition of formulas of residual deflection and load deflection, the formula of total deflection is

$$f_N = -0.06221 + 0.02691\frac{M_{max}}{M_{cr}\alpha_E\rho}\left[1.4726 + 3.1876\left(\frac{n}{N}\right)^{4.5851} + 3.6781\left(\frac{n}{N}\right)^{5.3997}\right] + \frac{\alpha M_{max}L^2}{B}\left[1.1798 + 0.6568\left(\frac{n}{N}\right)^{11.1347} + 0.1327\left(\frac{n}{N}\right)^{0.9877}\right] \quad (8)$$

The comparison of calculated results from Equation (8) and the test results of total deflection is shown in Figure 9. The test results of total fatigue deflection agree well with the calculated results from Equation (8).

5. CONCLUSIONS

To analyze the variation laws of deflection of prestressed concrete beams under overloads, the load deflection curves of prestressed concrete beams were analyzed based on the fatigue test. The calculation formulas of residual deflection and load deflection were derived from the fitting of the empirical formula. On this basis, the influencing factors of deflection parameters were analyzed. The following conclusions could be drawn:

(1) The vertical variations of concrete strain under overload basically conform to the plane hypothesis.

(2) The deflection of test beams generally undergoes three developmental stages: fast growth stage, stable growth stage, and violent fluctuation stage.

(3) The deflection variation laws of partially prestressed concrete beams under overload are basically similar with the curve linearity under normal operation loads. Deflection increases continuously with the increase of the upper limit of fatigue load and the number of loading cycles.

(4) Based on development characteristics of midspan deflection in the fatigue test, and the heavy-duty traffic characteristics, and the test data fitting, the calculation formula

of residual deflection and load deflection were obtained. On this basis, the calculation formula of total deflection was finally obtained. The calculated results agree well with the test results and can satisfy the requirements of accuracy in engineering application.

That is, the proposed calculation formula of deflection has a simple form and a few parameters and is easy to be determined. It can predict the deflection development of prestressed concrete beams under overload and lays the foundation for further analysis of the fatigue life of beam members after cracking. However, this study involves few test samples and the vehicle load conditions are complicated, which may cause certain discrepancy between the test results and actual situations. Future studies shall introduce the vehicle load coefficient into the formula to expand the range of application.

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