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An Rapid Assessment Method for Bearing Capacity of RC Girder Bridges Based on Residual Strain

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Abstract

In order to realize the *in-situ* evaluation of reinforced concrete bridges subjected to fatigue for a long time or after earthquake, an evaluation method for cumulative damage of concrete structures based on unloading elastic modulus was proposed. First, according to the concrete stress-strain curve and the statistical relationship between residual strain and cumulative strain, the calculation method of static equivalent strain and residual strain concrete based on unloading elastic modulus and the method for estimating the strength of concrete after damage were proposed. The detailed steps of field test and analysis and the practical damage indicators of residual strain were given. Then, the evaluation method of existing stress and strain of Reinforced Concrete Bridge under dead load and the concept of “equivalent dead load bending moment” were put forward. On this basis, the paper analyzed the root cause of the decrease of bearing capacity of Reinforced Concrete Bridge after fatigue damage, and pointed out that the equivalent strain or residual strain of reinforced concrete increases under the fatigue effect, which led to the decreasing of actual live moment and deformation performance while the ultimate load-carrying capacity remained constant or very little decrease. The evaluation method of structure residual capacity was given, and through comparative analysis of eight T reinforced concrete beams that had been in service for 35 years with the static failure tests, the effectiveness of the method was verified.

Keywords

Bridge Engineering, Reinforced Concrete, Fatigue Damage, Unloading Elastic Modulus, Residual Strain, Residual Bearing Capacity

1. Introduction

In recent years, with the frequent accidents worldwide caused by overloading of bridges and environmental erosion, the fatigue damage of bridges is becoming more and more serious. A large number of experimental studies on concrete beams show that [1]-[4], the failure characteristics of concrete beam under fatigue load generally behave as one or part of the tensioned main reinforcement fracture due to fatigue, and the bearing capacity of reinforced concrete beam after the failure will be significantly reduced. For the concrete beams without fatigue failure, the average strain of the cross-section is still in accordance with the assumption of plane section. The height of the compression zone in the cross-section is basically the same (related to the ceiling load). The concrete in the compression area is still in the elastic stage, and the fatigue elastic modulus of concrete decays continuously. The width of the concrete crack in the tension zone increases, resulting in the decrease of the flexural rigidity of the concrete beam, the increase of the residual deformation and the increase of the tensile steel stress. Therefore, the working state and remaining bearing capacity of concrete bridges without fatigue damage have become the research focus of the bridge sector.

In terms of assessing the bearing capacity of concrete bridges, China has formed a more perfect standard system, usually through structural detection combined with the calculation and analysis. The calculation method of bearing capacity adopted in the *Technical Code for the Detection and Evaluation of Urban Bridges* (CJJ/T 233-2015) is based on the test results of the bridge material and appearance, but the bearing capacity calculation of structures with more serious damage is still a difficult problem. The method of calculating the bearing capacity of the bridge is based on the test results of the bridge inspection and assessment. The "scoring" method is adopted by *The Testing and Evaluation Procedures of Highway and Bridge Carrying Capacity* (JTG/T J21-2011), which mainly depends on the bridge damage classification, the refinement and accuracy of scoring standards as well as the experience and technical level of detection personnel, and subject to the influence of subjective factors. Besides, the generally considered reliable method-load test is often used to verify the calculation result. However, the traditional static load test can only evaluate the bridge performance under the "test load", which is to evaluate the normal bearing capacity according to the change of the structural rigidity or the cross-sectional stiffness, and the bearing capacity is indirectly reflected by the elastic behavior. Thus, a contradiction emerges between conventional static load test and the actual bridge failure test; some bridges which are judged to have a decreasing bearing capacity or fail to meet the requirements by the conventional static load test, are tested to have the same bearing capacity as before by actual bridge failure test. For example, Zhang Jianren [5] carried out an on-site failure test for a 43-year long-term overloaded RC beam subjected to over-limit vehicle loading. The results show that cumulative fatigue damage has no significant effect on the static load-carrying capacity of the bridge. Structural response analysis shows that overload makes the mechanical behavior of the structure changes from elastic to plastic. Yu Zhiwu [6] and Sun Xiaoyan [7] also found through the experimental study that, when the fatigue failure doesn't happen on concrete beams, the corresponding fatigue residual capacity is almost unchanged. Therefore, they believed that fatigue cumulative damage mainly reduces the deformation properties of the structure, but has little influence on the bearing capacity of the structure, however, they don't further analyze the reason.

In terms of theoretical analysis, the present research mainly focuses on the analysis of structural damage accumulation and life prediction based on material damage. Wang Chunsheng [8] proposed an evaluation method for fatigue life of concrete bridges based on *S*-*N* curves and fracture mechanics. Zhu Jinsong [9] and Wang Qing [10] established the whole process analysis method of concrete bridges fatigue failure. The application process of the above-mentioned analysis method requires to know how the load works, but the functioning course of the actual bridge is often not clear, and the structure or the cross-section stress redistribution after the damage, and the effect of nonlinear coupling of fatigue, creep, temperature and shrinkage during service add more complexity to the evaluation of the cumulative damage degree of the existing structure concrete, the result obtained by simplified prediction of fatigue cumulative damage analysis is often different from the actual results. Therefore, in view of the urgent need of the engineering community to assess the cumulative damage of existing concrete bridges, an evaluation method that can directly determine the cumulative damage degree and residual bearing capacity is urgently needed.

In this paper, according to the measured elastic modulus of concrete after damage, the calculation method of equivalent strain and residual strain as well as the evaluation method of concrete strength after damage are put forward. Then, the structural analysis method is adopted for the evaluation of the existing stress, strain state and residual bearing capacity of the bridge.

2. Residual Strain Analysis Methods Based on Unloading Elastic Modulus of Concrete

According to the uniqueness assumption proposed by Sinha [11], the relationship between the load and the deformation will remain the same regardless of the repeated load history of the concrete, so long as the residual deformation is the same and the same repeated load is applied. This hypothesis has now been confirmed by many experiments, so the monotone loading stress-strain relationship can be used to show the fatigue envelope of concrete. The compressive stress-strain curves of concrete under fatigue loading are shown in **Figure 1**. On the basis of the constitutive relations of concrete under uniaxial compression provided by *Code for Concrete Structure Design* (herein after referred to as Code), the complexity of the energy dissipation law is deducted, that is to say, the loading deformation modulus E_f and unloading elasticity modulus E_r after concrete damage is assumed to be in the linear mode as shown in **Figure 1**.

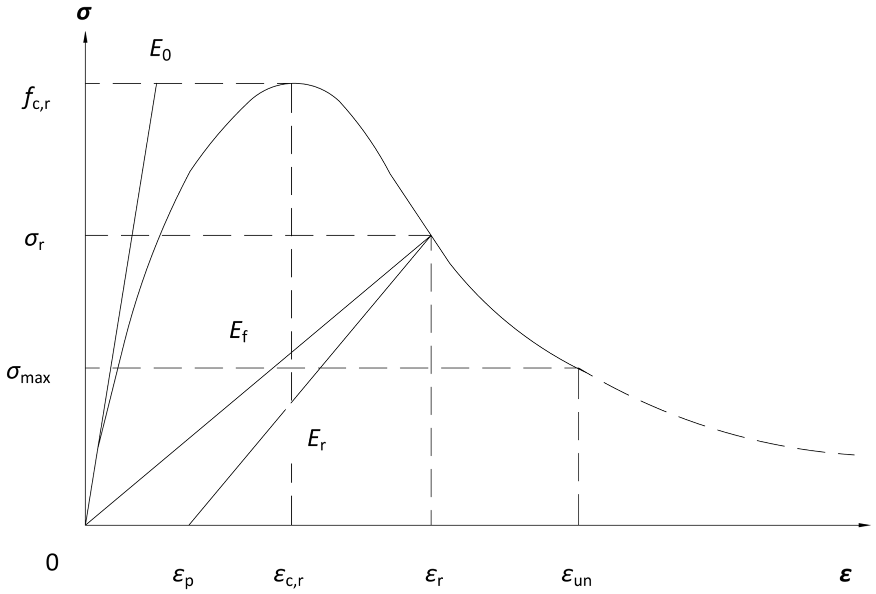

Figure 1. Stress-strain relations for concrete under pressure loading.

Many concrete fatigue tests show [12]-[14] that the damage and failure of concrete are internal microcracks extending to macroscopic cracks. When the crack length reaches a certain critical length, it will expand unsteadily until it breaks. And under various time-varying effects, the uniform internal damage of concrete is also caused by the expansion of micro-cracks inside the concrete, which results in deterioration of the mechanical properties of concrete [15]. The elastic modulus and the residual strain can reflect the microscopic damage mechanism of the concrete macroscopically, and have nothing to do with the loading history, which is a good choice for the concrete structure assessment. For various strength concrete, the development of fatigue residual strain is more stable and representative [13] [16], but it cannot be tested directly due to the time-varying effect, in consequence, the deformation modulus E_f cannot be measured either, only the elastic modulus of unloading concrete E_r can be tested on-site, however, there's still some limitations for the application of E_r [17]. It can be seen that the residual strain ε_p is related to the unloaded elastic modulus E_r and the static equivalent strain ε_r in **Figure 1**. Therefore, how to obtain the residual strain according to the unloaded elastic modulus has become the key to evaluate the cumulative damage of concrete.

Now the residual strain of concrete is basically analyzed by the test statistic method. The Berkeley loading and unloading model [18] illustrates the relationship between the residual strain ε_p and fatigue cumulative strain ε_r as shown in formula (1). The statistical formula shown in formula (2) is also derived by Guo Zhenhai [19]. The residual strain calculated by the Berkeley loading and unloading model is close to that calculated by the Guo Zhenhai model which is slightly larger.

$$\begin{cases} \left[\dfrac{\varepsilon_{\mathrm{r}}}{\varepsilon_{\mathrm{c,r}}}\right] < 2 & \dfrac{\varepsilon_{\mathrm{p}}}{\varepsilon_{\mathrm{c,r}}} = 0.145\times\left[\dfrac{\varepsilon_{\mathrm{r}}}{\varepsilon_{\mathrm{c,r}}}\right]^{2} + 0.13\times\left[\dfrac{\varepsilon_{\mathrm{r}}}{\varepsilon_{\mathrm{c,r}}}\right] \\ \left[\dfrac{\varepsilon_{\mathrm{r}}}{\varepsilon_{\mathrm{c,r}}}\right] \geq 2 & \dfrac{\varepsilon_{\mathrm{p}}}{\varepsilon_{\mathrm{c,r}}} = 0.707\times\left[\dfrac{\varepsilon_{\mathrm{r}}}{\varepsilon_{\mathrm{c,r}}} - 2\right] + 0.834 \end{cases} \tag{1}$$

$$\frac{\varepsilon_{\mathrm{p}}}{\varepsilon_{\mathrm{c,r}}} = 0.247\times\left[\frac{\varepsilon_{\mathrm{r}}}{\varepsilon_{\mathrm{c,r}}}\right]^{1.77} \tag{2}$$

Holmen [12] believes that "concrete ultimate strain can be used as criteria for concrete fatigue failure", a large number of fatigue test results also verify his point. Therefore, the maximum strain of concrete under fatigue loading is equivalent to the strain corresponding to the maximum stress of the monotone loading softening zone [20], such as $\varepsilon_{\mathrm{un}}$ in **Figure 1**, but this value is related to the maximum stress $\sigma_{\max}$ corresponding to the softening zone of the concrete and is difficult to accurately determine. "The fatigue residual stress ε_{p} is equal to $0.4\varepsilon_{\mathrm{c,r}}$" is generally recognized as the practical failure criterion for fatigue failure [2] [20]. The actual structure of the concrete stress is not uniform, the site of damage is often local. And structures which break this limit usually have serious cracking and can no longer be effectively used. Therefore, this failure criterion is also used in this paper. The relationship between residual strain and cumulative strain as shown in formula (3) is presented. The comparison with Berkeley loading-unloading model and oversea model is shown in **Figure 2**. It can be seen that the residual strain curve calculated by the relational expression is between the curve of the Berkeley loading-unloading model and the Guo Zhenhai model, which is close to the curve of Guo Zhenhai model, and also proves the rationality of the relational expression. When the concrete residual strain $\varepsilon_{\mathrm{p}} = 0.4\varepsilon_{\mathrm{c,r}}$, the corresponding cumulative strain is $1.3\varepsilon_{\mathrm{c,r}}$ according to the formula (3). When the concrete reaches the peak strain $\varepsilon_{\mathrm{c,r}}$, the corresponding $\varepsilon_{\mathrm{p}} = 0.25\varepsilon_{\mathrm{c,r}}$.

$$\frac{\varepsilon_{\mathrm{p}}}{\varepsilon_{\mathrm{c,r}}} = 0.186\times\left[\frac{\varepsilon_{\mathrm{r}}}{\varepsilon_{\mathrm{c,r}}}\right]^{2} + 0.067\times\left[\frac{\varepsilon_{\mathrm{r}}}{\varepsilon_{\mathrm{c,r}}}\right] \qquad \left[\frac{\varepsilon_{\mathrm{r}}}{\varepsilon_{\mathrm{c,r}}}\right] \leq 1.3 \tag{3}$$

Then combined with formula (3), the static equivalent strain analysis model of the cumulative damage of compressive concrete is established. The residual strain can be calculated by static equivalent strain and the stress and the strength of concrete after damage can be further inferred. Specific test and analysis steps are as follows:

Step 1: Using Non-destructive testing methods such as ultrasonic, blast wave or core sample method to test and analyze the mechanical parameters of non-destructive concrete in representative concrete member and parts, including the concrete compressive strength $f_{\mathrm{c,r}}$, the concrete elastic modulus E_{c} and the peak compressive strain $\varepsilon_{\mathrm{c,r}}$.

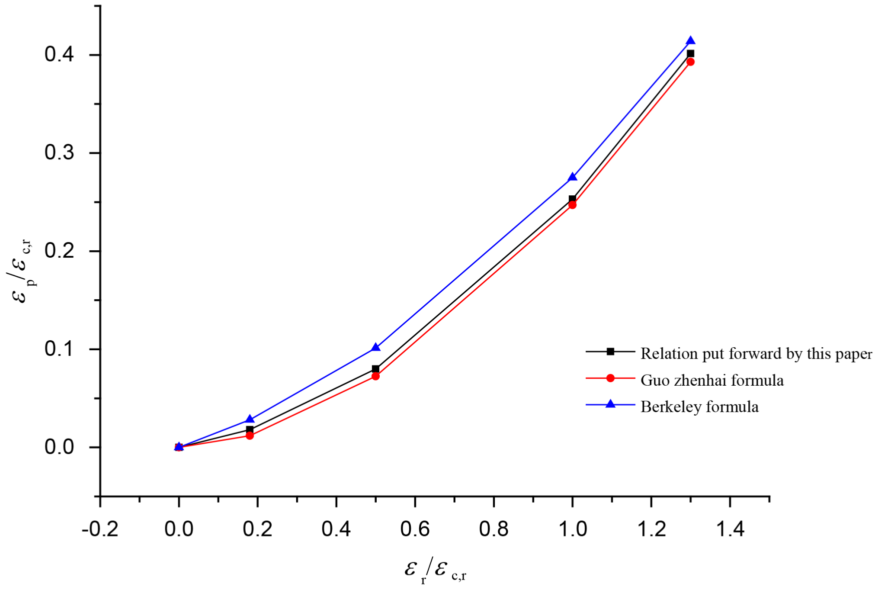

Figure 2. Concrete residual strain and fatigue cumulative strain relationship.

Step 2: The uniaxial compression stress-strain curve can be made according to the actual compressive strength of concrete $f_{c,r}$ and elastic modulus E_c, the formula is shown below:

$$\sigma = \left(1\text{-}d_c\right) E_c \varepsilon \tag{4}$$

where σ, ε are the compressive resistance and compressive strain of the concrete; d_c is the evolutionary parameter of the compression damage of the concrete. For details, see C.2.4 of the Code.

Step 3: The unloading elastic modulus E_r of the critical point of the structural concrete (usually the most unfavorable force section of the stressed member) can be measured by using the non-destructive testing method or the static loading and strain testing system; for example, by applying the static load to the structural concrete, the stress increment and strain increment of the concrete are obtained, and the unloading elastic modulus E_r is calculated according to formula (5).

$$E_r = \frac{\Delta\sigma}{\Delta\varepsilon} \tag{5}$$

In the formula, $\Delta\sigma$, $\Delta\varepsilon$ are the stress increment and strain increment of concrete under static loading respectively.

Step 4: The relationship between the unloaded elastic modulus E_r and the static equivalent strain ε_r is established according to **Figure 1**.

$$E_r = \frac{\left(1\text{-}d_c\right) E_c \varepsilon_r}{\varepsilon_r - \varepsilon_p} \tag{6}$$

Step 5: According to the relationship between residual strain and fatigue cumulative strain given by formula (3) and formula (6), the static equivalent strain

ε_r can be calculated.

Step 6: Calculate the static equivalent stress σ_r corresponding to ε_r according to equation (7), then the residual strain value ε_p of the concrete is obtained by formula (8):

$$\sigma_r = \left(1\text{-}d_\mathrm{c}\right) E_\mathrm{c}\varepsilon_\mathrm{r} \tag{7}$$

$$\varepsilon_\mathrm{p} = \varepsilon_\mathrm{r} - \sigma_r / E_r \tag{8}$$

Step 7: The residual strength of concrete after damage can be deduced according to the concrete stress-strain curve and static equivalent strain ε_r: when $\varepsilon_\mathrm{r} \le \varepsilon_\mathrm{c,r}$, the concrete strength remains to be $f_\mathrm{c,r}$; when $\varepsilon_\mathrm{r} > \varepsilon_\mathrm{c,r}$, the concrete strength decreases, the static equivalent stress σ_r calculated by formula (7) is the residual strength of the concrete after damage.

Step 8: The practical damage indices D_p and D_ε calculated based on the residual strain and static equivalent strain of concrete are shown in Equations (9) and (10), respectively. The comparison of D_p and D_ε applicability is shown in Figure 3. D_ε increases linearly with the increasing strain, but D_p can reflect the accelerated development of the damage when the strain is increasing, therefore D_p index is more reasonable.

$$D_\mathrm{p} = \frac{\varepsilon_\mathrm{p}}{0.4\varepsilon_\mathrm{cr}} \tag{9}$$

$$D_\varepsilon = \frac{\varepsilon_\mathrm{r}}{1.3\varepsilon_\mathrm{cr}} \tag{10}$$

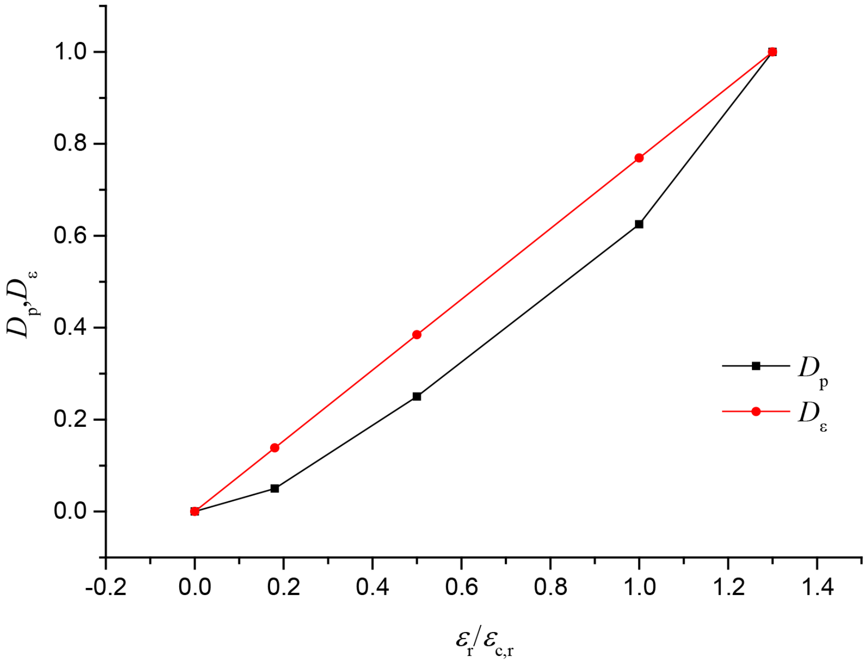

Figure 3. A comparison for concrete damage index between residual strain and static equivalent strain.

3. Practical Evaluation of Working State and Remaining Bearing Capacity of Reinforced Concrete Bridges

3.1. The Working Condition of RC Bridge under Constant Load

According to the above analysis and evaluation of residual strain of concrete, the existing stress and strain state of reinforced concrete beams can be evaluated under the assumption of plane section. In order to consider the effect of residual strain, the concept of "equivalent dead load moment" is put forward to distinguish with the original dead load moment and to evaluate the residual bearing capacity of reinforced concrete beam. Take the common T-section reinforced concrete bending members as an example, as shown in **Figure 4**, the specific analysis steps are as follows:

Step 1: According to the practical failure criterion of concrete fatigue failure, the residual strain ε_p at the edge of compression area are compared with $0.4\varepsilon_{c,r}$, and the damage boundary of reinforced concrete beam is evaluated by the residual strain ε_p of the concrete:

1) When the concrete residual strain $\varepsilon_p > 0.4\varepsilon_{c,r}$, reinforced concrete beams are damaged seriously and often do not have the value of maintenance and reinforcement, assessment is no longer carried out;

2) When the concrete residual strain $\varepsilon_p \leq 0.4\varepsilon_{c,r}$, the working state of reinforced concrete beams should be evaluated.

Step 2: When the concrete residual strain $\varepsilon_p \leq 0.4\varepsilon_{c,r}$, according to $\sigma_e = M_g Z_c / I_{cr}$, the concrete elastic stress σ_e in the stress zone of cross-section under constant load can be obtained. Where M_g is the constant load moment of the cross-section; I_{cr} is the converted moment of inertia, Z_c is the measured height of cross-section pressure zone.

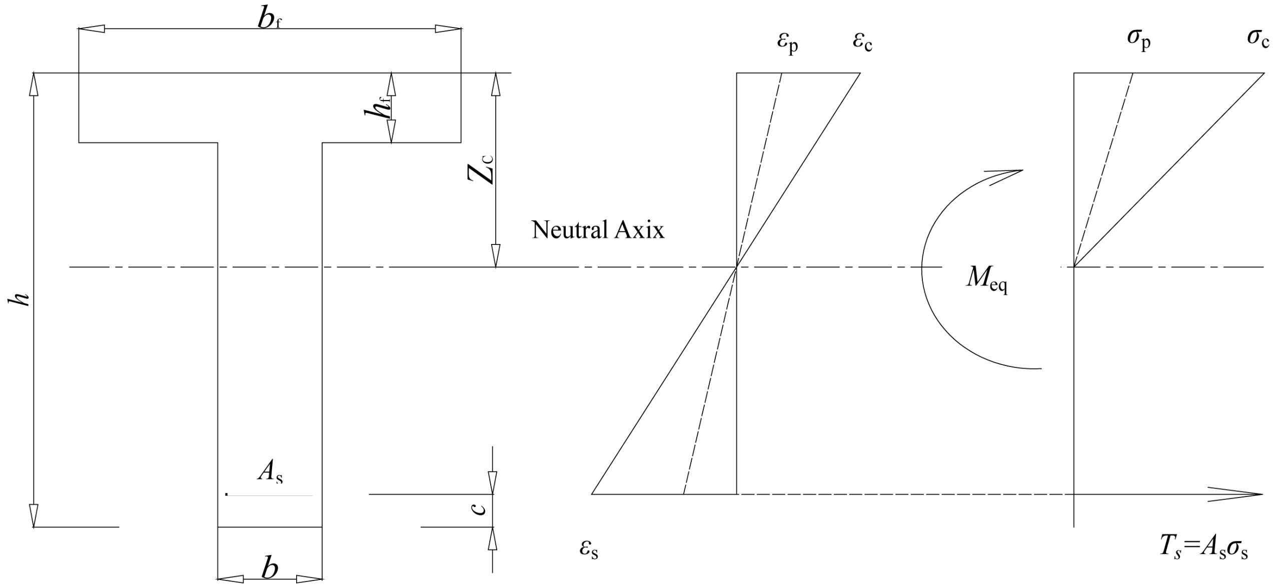

Figure 4. The actual strain distribution and the equivalent bending moment of RC beams.

Step 3: According to $\varepsilon_e = \sigma_e/E_r$, the concrete elastic strain ε_e can be obtained, and according to $\varepsilon_c = \varepsilon_e + \varepsilon_p$, the concrete total strain ε_c can be obtained as shown in **Figure 4**.

Step 4: The total strain ε_s of the tensioned longitudinal reinforcement is obtained from $\varepsilon_s = \varepsilon_c \times (h - c - Z_c)/Z_c$, and the elastic modulus of the tensioned steel is basically the same as the elasticity of the tensile steel still works under fatigue loading, and the reinforcement tensile stress can be obtained by $\sigma_s = E_s \times \varepsilon_s$. Considering the influence of non-closed fracture, the actual stress is obtained by multiplying the calculated stress with the increase coefficient of 1.1 - 1.2 [2] [3]. Where c is the thickness of the concrete protective layer in the tension zone; h is the height of the section.

Step 5: The "equivalent static moment" M_{eq} can be obtained approximately from $M_{eq} = A_s \times \sigma_s \times 0.9h_0$ (rectangular cross-section taken $0.87h_0$). Where, M_{eq} is the equivalent bending moment of the mid-span section under the influence of the residual strain of the concrete under the constant load (after the longitudinal reinforcement stress increases), which is obviously greater than or equal to the actual dead load moment M_g; A_s is the cross-sectional area of tensioned longitudinal reinforcement; h_0 is the effective cross-section height, $h_0 = h - c$.

Step 6: For the sake of simplicity, it is safe to approximate the stress-strain curve of the concrete in the dead zone to a triangular shape, as shown in **Figure 4**, and the equivalent compressive stress σ_c under constant load can be obtained by $\sigma_c = M_{eq} Z_c/I_{cr}$.

Following the above steps, the ultimate bearing capacity and residual bearing capacity of reinforced concrete bridges after fatigue damage can be further analyzed. The results show that the ultimate load-carrying capacity of reinforced concrete bridges is higher than that of concrete beams.

3.2. Residual Bearing Capacity of Reinforced Concrete Bridges after Fatigue Damage

Experiments have shown [5]-[7] that fatigue damage has little effect on the ultimate load-carrying capacity of the bridge, and the ultimate bearing capacity does not decrease or decrease very little, even increases due to the enhancement of yield strength of longitudinal reinforcement, exceeding the bearing capacity evaluated by the static load test. The reason is that the ultimate bearing capacity is controlled by the material properties and the section size of the concrete and the longitudinal reinforcement. If the material properties and the cross-sectional dimension are not changed or the degradation is very small, the ultimate bearing capacity of the reinforced concrete bridge will basically remain the same or show a very little decline. The experimental study and analysis of reinforced concrete members considering low-cycle fatigue have also proved that when the longitudinal reinforcement yielded but did not enter the descending section of the load-deformation curve, the degradation of yield strength and ultimate bearing capacity of the members caused by low-cycle fatigue damage [21] [22] is very small. Only when it goes into the descending section of the load-deformation curve, will the bearing capacity decrease gradually, while the low cycle fatigue has a greater influence on the deformation performance. In the use stage, the reinforced concrete bridge can hardly enter the descending section of the load-deformation curve. The serious damage of the compression concrete often accounts for a small area of the whole section, so the ultimate bearing capacity is almost unchanged. And now according to the traditional static load test, the bearing capacity is just the normal carrying capacity in the use stage, which is far less than the ultimate carrying capacity. Based on the above analysis, the bearing capacity after fatigue damage can be assessed based on the degradation of material properties, without considering the size of the cross-section and the impact of corrosion, the T-shaped section shown in **Figure 4** can still be used as an example to illustrate the practical evaluation process.

First of all, the ultimate bearing moment M_{jj} without fatigue cumulative damage and the bearing moment M_{dc} in service stage can be calculated based on the measured concrete compressive strength $f_{c,r}$ and the actual cross-section size of reinforced concrete beams. The ultimate bearing moment M_{jj} is calculated as shown in Equations (11) and (12). The calculation formula of the maximum loading moment M_{dc} is the same as the formula of the ultimate load moment M_{jj}, except that the standard value is substituted by the design value of concrete and longitudinal reinforcement.

$$\text{When } f_{sk}As \le f_{c,r}b_f h_f, M_{jj} = f_{c,r}b_f h_f\left(h_0 - h_f/2\right) \tag{11}$$

$$\text{When } f_{sk}As > f_{c,r}b_f h_f, M_{jj} = f_{c,r}\left[bx\left(h_0 - x/2\right) + \left(b_f - b\right)h_f\left(h_0 - h_f/2\right)\right] \tag{12}$$

where b_f is the effective width of the compression flange of the T-section; h_f is the effective thickness of the compressed flange of the T-section; b is the width of the T-section web, f_{sk} is the standard value of the tensile strength of the longitudinal reinforcement, x is the height of the compression zone when the section is broken.

Then, according to the practical failure criterion of concrete fatigue failure, whether concrete strength after concrete damage is reduced is judged by static equivalent strain or residual strain of concrete, the actual ultimate bearing moment M_{zj} of reinforced concrete beam after fatigue damage and the bearing moment M_{zc} can be evaluated:

$$\begin{aligned}&\text{When } \varepsilon_r \le \varepsilon_{c,r} \text{ or } \varepsilon_p \le 0.25\varepsilon_{c,r}, \text{the concrete strength is not changed,}\\&M_{zj} = M_{jj}, M_{zc} = M_{dc}\end{aligned} \tag{13}$$

$$\begin{aligned}&\text{When } \varepsilon_{c,r} < \varepsilon_r \le 1.3\varepsilon_{c,r} \text{ or } 0.25\varepsilon_{c,r} < \varepsilon_p \le 0.4\varepsilon_{c,r}, \text{the concrete strength}\\&\text{decreases}, M_{zj} = 95\%M_{jj}, M_{zc} = 95\%M_{dc}\end{aligned} \tag{14}$$

It should be noted that, according to the existing experimental study [7] [22], the reduction of ultimate bearing capacity caused by fatigue damage is generally less than or equal to 5%, so the bearing capacity reduction coefficient can be taken as 95%. The evaluation of bridge bearing capacity generally requires the live load of the structure as a basis for assessing its capacity to withstand overload (overload does exist) or set limit load. The maximum live load moment M_{hj} can be obtained by $M_{hj} = M_{zj} - M_{eq}$. The corresponding safety factor should be considered in the calculation of the maximum bending moment M_{hc}, according to the load factor valuation set by the bridge specification [23], $M_{hc} = (M_{zc} - 1.2M_{eq})/1.4$.

4. Case Analysis for Bearing Capacity of Old Reinforced Concrete Beams

Feng Zeying [24] carried out load failure test on 8 old T-shaped beams in 2004 that had been in use for 35 years in Mang Niu River Bridge, Liaoning Province, China. The cross-section and three-point static loading test diagram of the beams was shown in **Figure 5**. The cross-section geometric size of the beams and the measured compressive strength of the concrete were listed in **Table 1**, main bearing bar in beams was $8\Phi 28 + 4\Phi 16$, which measured mean yield strength was 335 MPa. The damage of 8 old beams was mainly manifested by vertical through cracks near the mid-span bending area, and the measured crack characteristics under dead load were shown in **Table 2**.

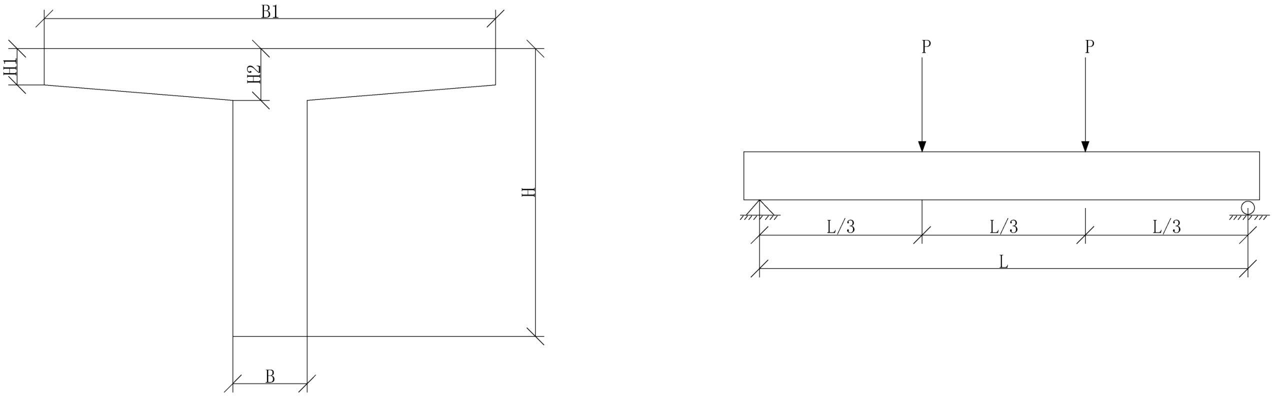

Figure 5. The cross-section of the beam and the diagram of the three-point loading test.

Table 1. Cross-section geometric size and concrete compressive strength of beams.

Beam code	H /cm	B /cm	B1 /cm	H1 /cm	H2 /cm	Beam length L/m	Concrete Strength/MPa
1#	135	18	110	10.3	15.5	22.14	27.92
2#	135	18.5	135	8	15.5	22.14	27.61
3#	135	18	130	8	15.5	22.23	31.27
4#	136	18.5	107	11	18	22.18	24.61
5#	134	18.4	130	11	17	22.16	26.29
6#	135	18.9	115	11	18	22.16	23.78
7#	136	18.5	134	7.5	16	22.16	26.85
8#	134	18	80	8	14	22.16	26.27

Table 2. Crack width and relative height of beams under dead load.

Crack characteristics	1#	2#	3#	4#	5#	6#	7#	8#
Maximum crack width/mm	0.15	0.15	0.12	0.4	0.25	0.15	0.15	0.2
Crack relative to beam height	0.615	0.533	0.556	0.735	0.896	0.504	0.444	0.704

Although the old ordinary reinforced concrete beams had serious cumulative fatigue damage, the ultimate bending capacity calculated based on the measured material data and the actual section size is very close to the text breaking moment in Table 3. Among them, the maximum deviation rate of beams is only 7.3%, indicating that the cumulative fatigue damage has little effect on the ultimate bearing capacity of reinforced concrete beams.

Table 3. Calculated ultimate bending capacity and yield load comparison with the test.

Beam code	Ultimate bending capacity comparison				Yield load comparison			
	Failure load of test /kN	Failure bending moment/ kN·m	Calculated ultimate bending moment /kN·m	Deviation rate/%	Yielding load of test/kN	Equivalent additional load/kN	Calculated yielding load/kN	Deviation rate/%
1#	360	2021.8	2025.4	0.2%	320	15.6	323.6	1.12
2#	350	2052.5	2032.9	1.0%	320	0	327.2	2.25
3#	375	2126.9	2066.0	−2.9%	320	0	332.9	4.03
4#	320	1926.4	1988.1	3.2%	290	44.58	286.42	−1.23
5#	346	2091.9	2014.8	−3.7%	290	19.73	303.77	4.75
6#	366	2127.1	1983.7	−6.7%	320	0	324.1	1.28
7#	358	2079.2	2022.6	−2.7%	320	0	327.5	2.34
8#	358	1861.4	1997.1	7.3%	320	44.36	311.54	−2.64

Considering the accurate loading value of the test beam at yielding and the essentially linear load-deflection curve before yielding, these yielding load values are selected to verify the rationality of the evaluation method in this paper. Among these beams, 2#, 3#, 6# and 7# exhibit bending cracks with a relative height of less than 0.6, indicating that the concrete in the compression zone is primarily in an elastic working state with minimal residual strain effect. On the other hand, beams 1#, 4#, 5# and 8# show significant decline, allowing for calculation of their equivalent additional load under dead load based on residual strain analysis. The calculated load values at yield deviate from test results by less than 5%. This simplified evaluation method meets engineering accuracy requirements and is particularly suitable for quantitatively assessing bearing capacity in reinforced concrete beams with severe fatigue damage.

Based on the above analysis, the ultimate load-carrying capacity of reinforced concrete bridges after fatigue damage has not decreased or decreased very little. And the reason why it is generally believed that the bearing capacity of the structure decreases under the fatigue damage is that the structural concrete strain, residual strain are increasing under fatigue effect, so that the “equivalent dead load moment” of the cross section is greater than the dead load moment, in consequence, the actual live load bending moment is reduced.

5. Conclusions

1) According to the practical relationship among concrete stress-strain curve, residual strain and accumulated strain, the calculation method of concrete equivalent static strain and residual strain based on unloading elastic modulus is put forward, and the specific testing and analysis steps of concrete structure site are detailed described, which is applicable for the acquisition of fatigue cumulative strain and residual strain of structural concrete.

2) A proposed analysis method for reinforced concrete bridges involves considering the effect of residual strain on the “equivalent bending moment under constant load”, and it’s applicable for the working state rapid evaluation of existing reinforced concrete bridges.

3) The main reason why the residual capacity of Reinforced Concrete Bridge is basically invariable or declining after fatigue damage is analyzed, and the practical evaluation method of residual capacity of structure is given. It points out that the main reason is that the equivalent strain or residual strain of structural concrete increases under the influence of fatigue, resulting in the decline of the actual live load level that the bridge can bear.

6. Discussion

The research on the evaluation method of bearing capacity of reinforced concrete bridges after fatigue damage is discussed above, which is applicable for the *in-situ* evaluation of concrete bridges. This simplified evaluation method meets engineering accuracy requirements and is particularly suitable for quantitatively assessing bearing capacity in reinforced concrete beams with severe fatigue damage.

The influence of longitudinal reinforcement ratio, concrete strength and prestressing effect is not analyzed in this paper. In addition, the concrete residual strain analysis method and the damage index can be used to evaluate the deformation performance of concrete bridge, and the analysis and evaluation of the deformation behavior after damage are worthy of further study.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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