FATIGUE DAMAGE MODEL OF RC BEAMS STRENGTHENED WITH CFL BASED ON STIFFNESS DEGRADATION

C. Zhao and P.Y. Huang

College of Traffic & Communications, South China Univ. of Tech., China

ABSTRACT

Carbon Fiber Laminate (CFL) strengthened RC beam is the combination of steel, concrete and CFL, so its fatigue mechanism is very complex. According to the rule of stiffness evolution under cyclic load, the damage was defined by residual flexural stiffness of strengthened beam. A method for dynamic flexural rigidity of beams that can account for the coupling action between concrete, reinforcement and Carbon Fiber Laminate (CFL) is proposed. Based on the stress analysis of cross-section, piecewise linear method takes account for the stress redistribution in fatigue damage process caused by the difference between damage mechanisms of concrete and reinforcement. Using this method, the fatigue damage evolution of strengthened members was simulated and can predict the fatigue lives of Strengthened RC beams.

KEYWORDS

Fatigue damage model, cyclic loading, carbon fiber laminate, RC beams, stiffness.

INTRODUCTION

Fracture led by fatigue is one of the major reasons of structure damage, so it is necessary to have a deep study on the endurance and fatigue damage with CFL (Carbon Fiber Laminate) strengthened RC component. The bridge load is mainly from vehicle load, so research on the fatigue performance of CFL strengthened RC component can give the evidence for the assessments to the fatigue life of the CFL strengthened RC bridge. Although lots of experts all over the worlds have done a great deal of tests and theory analysis about strengthening the reinforced concrete beams by using CFRP, there is few further research on fatigue performance of RC beams strengthened with CFRP (e.g. Meier 1992, Inoue 1994, Shahawy 1999, Barnes 1999, Aidoo 2004, Heffernan 2004).

CFL strengthened RC beam is the combination of steel, concrete and CFL, so its fatigue mechanism is complex and nonlinear. One of the damage makes the effect on the loaded state of the combining beam and further change the stress distribution on the section. But the current calculation method doesn’t fully cover the coupling effect, compared with variable amplitude loading on the RC beam in the reality engineering; it focuses on the fatigue with constant amplitude loading.

Based on the stress analysis of cross-section, a method for fatigue damage nonlinear analysis of beams that can account for the coupling action between concrete and reinforcement is proposed. This method takes account for the stress redistribution in fatigue damage process caused by the difference between damage mechanisms of concrete and reinforcement and can predict the fatigue life of beams strengthened with CFL.

RESIDUAL STIFFNESS MODEL

Along with the cycles increase, the fatigue performance of the RC beams was decreasing under the cyclic loading. The damage of the concrete accumulation and deformation was enlarged, and then the tensile zone cracked soon. The adhesive stress between the steel, CFL and concrete degenerated and the slippage increased, thus, the flexural stiffness of the strengthened beam degenerated along with the cycle load. Because the stiffness is absolute value, the stiffness differs from the beams. So the relative damage can be used to quantify the damage of the beams. Similar to the damage equation of the Lemaitre, the damage was defined by residual flexural rigidity of strengthened beams, such as:
\[ D_N = 1 - \frac{B_N}{B_0} \]  

(1)

Which \(B_0\) is initial stiffness and \(B_N\) is dynamic stiffness after \(N\) cycles. The flexural stiffness was degrading with the increasing cycles \(N\) (Niu 2004), and can be divided into three phases: 1) Quick degradation phase: occupy about 5% fatigue life; 2) Stable phase: occupying about 5%–99% fatigue life; 3) Failure phase: occupying about 1% fatigue life. Analyzing the rule of the stiffness degradation, average stiffness of the four group beams before failure is \(0.71B_N/B_0\), and the standard deviation was 0.04. \(B_0\) is initial stiffness. Because the failure phase is occupied only 1% fatigue life, the life of the beam can be taken as the life when the stiffness degrade to 0.77\(B_0\).

**DAMAGE EVOLUTION OF MATERIALS**

**Concrete**

The results indicate the concrete elastic modulus degraded with the increase of the cycles. Based on the deformation developing law of compress area, flexure deformation modulus \(E_b\) was taken as fatigue damage variables. The degradation of the deformation modulus can not be calculated by the old documents. To overcome the shortcomings above, the accumulated residual strain \(\varepsilon_{cr}\) is reasonable selection since it can describe the concrete deformation modulus. According to the development rule of the fatigue strain in compress

According to developing law of accumulated residual strain, equation (2) is used to calculate flexure deformation modulus after \(N\) cycles:

\[ E_b^f(N) = \beta \cdot \frac{\sigma_{\varepsilon_{max},i}^f}{\sigma_{\varepsilon_{max},i}^f / E_b + \varepsilon_{cr}} \]  

(2)

Where residual strain \(\varepsilon_{cr}\) can be found as equation (3):

\[ \varepsilon_{cr} = \frac{f_c}{E_b} \left[ \sum_{i=1}^{n_f} \frac{n_i}{N_i} \log(13.52 \alpha_{cr,i} - 16.07)^b \right] \]  

(3)

\(\alpha_{cr,i}\) is stress range ratio of No. \(i\) stage and is given by:

\[ \alpha_{cr,i} = \frac{\sigma_{\varepsilon_{max},i}^f - \sigma_{\varepsilon_{min},i}^f}{f_c - \sigma_{\varepsilon_{min},i}^f} \]  

(4)

\(\sigma_{\varepsilon_{max},i}^f\) is the maximum stress of concrete compress area and \(\sigma_{\varepsilon_{min},i}^f\) is the minimum stress of concrete compress area when stress stage is \(i\).

**Steel**

Area of steel accord with subsection linearity accumulate damage, hence the steel area under the cycle stress is given by:

\[ A_s^f(N) = A_s \cdot \prod_{i=1}^{n_f} \left[ 1 - \frac{n_i}{N_i} \left( 1 - \frac{\sigma_{\varepsilon_{max,i}}^f}{f_s} \right) \right] \]  

(5)

Where \(n_i\) is cycles of No. \(i\) stage; \(N_i\) is the fatigue life of No. \(i\) stage which can be obtained from \(S-N\) curve.

According to experiments, \(S-N\) curve of steel was given by Zeng(1999).

\[ \begin{align*}
\log N &= 15.1348 - 4.3287 \log \Delta \sigma; \quad N < 10^7 \\
\log N &= 18.847 - 6.3827 \log \Delta \sigma; \quad N \geq 10^7
\end{align*} \]  

(6)

**Carbon Fiber**

Compared with the other engineering materials, continuous carbon fiber reinforced composites have better fatigue properties and linear stress-strain relation. So in this paper, the ultimate strength of carbon fiber is considered as constant value under the cycle load.

**CALCULATION METHOD OF DYNAMIC STIFFNESS**

The fatigue damage of concrete members is a nonlinear process; however linear method is generally adopted. Therefore it is necessary to research the nonlinear analysis method. Based on the stress analysis of cross-section, piecewise linear method is used to realize the nonlinear solution process. In every increment of fatigue load, the section and materials properties keep the same and use the linear elastic method. Before calculating the next piecewise, the cross section and materials properties which base on the different damage mechanism will correct.
Consequently the aim for nonlinear analysis can be achieved. Piecewise step is chosen by different precision, usually $\Delta N$ is 10000.

Based on the analysis above, basic assumptions are given as (Figure 1):
(a) Section keeps plane;
(b) Steel area is adopted as the steel damage and the flexure deformation modulus is adopted to token the concrete damage.

According to the equilibrium condition of forces and moments, equations are gained:

\[
\begin{align*}
A'_{f}(N) \cdot E_{s}(h-x_{0}) + bE_{f}(h-x_{0} + \frac{f}{2}) + \int_{0}^{h-x_{0}} bE_{f}ydy - \int_{0}^{h} b \cdot E_{f}'(N) \cdot ydy &= 0 \quad (7) \\
A'_{f}(N) \cdot E_{s}(h-x_{0})^{2} + bE_{f}(h-x_{0} + \frac{f}{2})^{2} &+ \int_{0}^{h-x_{0}} bE_{f}y^{2}dy + \int_{0}^{h} b \cdot E_{f}'(N) \cdot y^{2}dy - M &= 0 \quad (8)
\end{align*}
\]

\[\begin{align*}
\text{Figure 1. Strain and stress diagram of strengthened beam}
\end{align*}\]

$A'_{f}(N)$ and $E_{f}'$ can be calculated by equation (2) and (3). $I'_0$ is conversion inertial moment and can be obtained by:
\[
I'_0 = \frac{bx_a^3}{3} + \alpha_{f}A'_f(h - x_0)^2 + \alpha_{b}A'_b(h_0 - x_0)^2 + \alpha_{c}A'_c(x_0 - a)^2 
\]

The dynamic stiffness of the beam strengthened with CFL is:
\[
B_N = E_f'I'_0 
\]

Because flexure deformation modulus and steel area are changed while the cycle is increasing, the calculation method given above is considered the stress redistribution of section conveniently and can be realized the nonlinear analysis. The stiffness calculated by equation (10) is changed when the cycles are increasing. The calculation process is:

a) Calculate the $M_{f_{\max}}$, $M_{f_{\min}}$ and repeat cycles $n_i$ ($i=1,2,\ldots,m$) at control section;

b) Calculate $\sigma_{f_{\max}}, \sigma_{f_{\min}}, \sigma_{s_{\max}}, \sigma_{s_{\min}}, \sigma_{f_{\max}}, \sigma_{f_{\min}}$;

c) According to equation (10), stiffness is account, and then estimate. If $B_N \geq 0.71B_b$, fatigue failure will occur, the fatigue life of beam is $N = \sum n_i$ and the calculation is over. Otherwise go on.

d) Use equation (2), (3) and (10) to calculate $E_f', \varepsilon_c'$ and $I'_0$, then return a) to calculate next round.
EXAMPLES AND DISCUSSIONS

The specimen is under three point bending load with 1850×100×200mm in size (Figure 2). CFL was attached to the tension area at beam bottom. The thickness of CFL is 0.5mm, and the strength is 3000Mpa. In the experiments, three sets of co-relative implements including the computer, Strain Test System, and MTS 810 were used in order to collect automatically the accurate data of the load and displacement of the specimen. In the fatigue tests, the force mode was taken to load with frequency of 10Hz. Then the experimental data such as the peak and valley load, cycles, the strain of the CFL and RC beams, the specimen span centre deflection etc. are recorded automatically by the test system. Stress ratio was 0.2 and $M_{\text{max}}$ was 12kN.m.

According to calculation process above, attenuation of stiffness along with the cycles were derived, as Fig.3. The first and second attenuation law was well calculated from the figure. When $M_{\text{max}}=12$kN.m, the fatigue life calculated was 690 thousands and experiments data was 780 thousands, discrepancy was 11.5%. Based on the experiment data that the beam deformation increased with cycles, Taiyuan (1981) used statistics analysis method to calculate the reducing coefficient of stiffness. According to Figure 3, the results calculated by Taiyuan (1981) were low and it could not calculate the stiffness under the random load.
result. The maximum strain was less than the ultimate strain of CFL, so the CFL could not snap first, and it was confirmed by experiments.

CONCLUSIONS

Based on the analysis of stiffness degenerated, the damage was defined by residual flexural stiffness of strengthened beams. A method for dynamic flexural stiffness of beams that can account for the coupling action between concrete, reinforcement and Carbon Fiber Laminate (CFL) was proposed. This piecewise linear method took account for the stress redistribution in fatigue damage process caused by the difference damage mechanisms piecewise linear method takes account for the stress redistribution in fatigue damage process caused by the difference damage mechanisms between concrete and reinforcement. Using this method, the fatigue damage evolution of strengthened members was simulated and can predict the fatigue lives of Strengthened RC beams. Discreteness of fatigue experiments is very big, so precise analysis is difficult, and the precision relate with the damage evolution of materials. It is necessary to precede relevant experiments.

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