EXPERIMENTAL ANALYSIS ON SEISMIC DAMAGE AND CREEP OF FRP RETROFITTED RC COLUMNS AFTER SIMULATED EARTHQUAKE TESTING

Bo SHAN
Associate Professor
Hunan University
Yuelushan, Changsha, Hunan 410082, China
supershanb@163.com

Yan XIAO
Professor
University of Southern California
Los Angeles, CA 90089, USA
xiaorock@yahoo.com

Abstract
This paper addresses residual seismic behavior of reinforced concrete (RC) columns retrofitted with fiber-reinforced plastic (FRP), which received little attention. Eight model columns were tested first under cyclic lateral force and a constant load equal to 20% of the column gross axial load capacity. Five of the model columns were subjected to long-term axial loading after subjected to limited damage by lateral cyclic loading. The deformation of retrofitted columns under long-term axial loading depended on the previous damage intensity and the modulus of FRP. Under the testing condition of this study, the long-term axial deformation of retrofitted column tends to be stable. The analytical studies were carried out using the age-adjusted effective modulus method for creep of concrete, combined with the Findley’s power law function for creep of FRP jacket. The model considered the effects of damaged degree of earthquake, sealed concrete, multi-axial state of stresses and stress redistribution. The model was verified against the long-term test in this paper.

Keywords: seismic retrofit; FRP; earthquake damage; residual performance; creep

1. Introduction
Numerous existing structures, particularly bridges in California and elsewhere, have been seismically upgraded with FRP wrapped. Retrofit design is based on the philosophy of enabling the structures to survive essentially one extreme seismic event. A retrofitted column is reasonably guaranteed to develop a ductile response to a severe earthquake attack. However, the post-earthquake health and the duration without failure of the damaged columns related to the time-dependent behaviour of the retrofitting system. These issues are of significant importance. It has been suspected that the rupture of several GFRP jackets installed on the columns of the I-5 and Freeway 2 interchange in Los Angeles was due to the insufficient residual capacity after the columns were subjected to the shaking of the 1994 Northridge earthquake. In this case, prestressing the FRP for active confinement of the concrete also compounded the problem (Hipley 2004). This paper presents an analytical method and some results for time-dependent study of damaged RC columns with FRP retrofitted.

Research on the long-term performance of FRP retrofitted columns is rare. Naguib and Mirmiran (2002, 2003) studied the time-dependence behaviour of concrete filled FRP tubular columns and fiber-wrapped concrete columns under axial load. Their research showed that the
creep deformation of FRP confined concrete column was much less than that recommended by ACI209 (1971, 1992), and no strength degradation was observed after long-term loading. It should be indicated that while the long-term loading used in this study is similar to that used by Naguib and Mirmiran (2002), the research objectives are distinctly different.

2. Experimental Program

2.1 Model Column Specimens and Lateral Loading Test

Eight RC model columns were tested with two steps in this project. Firstly, all model columns were tested first under cyclic lateral force. Secondly, five of the model columns were subjected to long-term axial loading after subjected to limited damage. The circular column had a diameter of 375mm and a height of 1500mm. CFRP and GFRP were used for the retrofitted RC columns. The testing matrix is shown in Table 1. The details of model columns and the test data of lateral loading test were presented in reference [5] (Shan and Xiao, 2006).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$f'_c$ (MPa)</th>
<th>Retrofit</th>
<th>Damage Due to Lateral Loading</th>
<th>Testing Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA-1</td>
<td>34.0</td>
<td>—</td>
<td>Failure at Drift Ratio $\Delta u/L=6%$</td>
<td>Lateral Loading Only</td>
</tr>
<tr>
<td>CA-2L</td>
<td>35.0</td>
<td>—</td>
<td>$0.5 \times \Delta u/L$</td>
<td>Lateral Loading and Long-term Test</td>
</tr>
<tr>
<td>CCR-1</td>
<td>30.9</td>
<td>4-layer CFRP</td>
<td>Failure at Drift Ratio $\Delta u/L=8%$</td>
<td>Lateral Loading Only</td>
</tr>
<tr>
<td>CCR-2L</td>
<td>38.6</td>
<td>4-layer CFRP</td>
<td>$0.375 \times \Delta u/L=3%$</td>
<td>Lateral Loading and Long-term Test</td>
</tr>
<tr>
<td>CCR-3L</td>
<td>41.4</td>
<td>4-layer CFRP</td>
<td>$0.75 \times \Delta u/L=6%$</td>
<td>Lateral Loading and Long-term Test</td>
</tr>
<tr>
<td>CGR-1</td>
<td>38.7</td>
<td>5-layer GFRP</td>
<td>Failure at Drift Ratio $\Delta u/L=10%$</td>
<td>Lateral Loading Only</td>
</tr>
<tr>
<td>CGR-2L</td>
<td>34.9</td>
<td>5-layer GFRP</td>
<td>$0.3 \times \Delta u/L=3%$</td>
<td>Lateral Loading and Long-term Test</td>
</tr>
<tr>
<td>CGR-3L</td>
<td>37.9</td>
<td>5-layer GFRP</td>
<td>$0.6 \times \Delta u/L=6%$</td>
<td>Lateral Loading and Long-term Test</td>
</tr>
</tbody>
</table>

2.2 Setup of Long-Term Test

As shown in Table 1, after imposing limited lateral loading damage to a certain peak drift level, model columns A-2L, CCR-2L, CCR-3L, CGR-2L and CGR-3L were subjected to sustained long-term axial loading to study the residual performance of damaged columns. Five sets of long-term axial loading setups as shown in Fig.1 were manufactured for such testing purpose. The test setup included a 200 ton hydraulic jack, a cross beam and two high-strength steel rods with a diameter of 50mm. The fluctuation of the load application was monitored using vibrating wire gauges which were mounted on the high-strength steel rods. The load application can be adjusted with manually controlled hydraulic pump.

3. Long-Term Loading Experimental Results

3.1 Long-Term Loading Test Method

Several measurement target staffs were fixed on the test columns as shown in Fig.1. Through measuring the varying distance of the measuring staffs on test column using a manual dial gauge, the radial deformation and axial deformation of the test column can be obtained. All the specimens were initially loaded at an axial load level equal to $0.2AF_{c'}$, and observed for 30 days when the deformation became sufficiently stable. The axial load was then removed and reapplied at a higher axial load level of $0.4AF_{c'}$, for a period of 60 days. This adjustment of axial load level was for an attempt to intensify the effects of axial loading, and did not
necessarily reflect any actual loading condition. During the entire course of the long-term loading tests, no apparent physical change was observed for the model columns.

Figure 1 Long-term axial loading test setup

3.2 Seismic Damage Analysis

Seismic damage can increase the deformation of test columns under long-term loading. So the double-parameter damage model, presented by Park and Ang (1985), is selected to analyze the degree of damage. This damage model is shown in Eq. 1.

\[ D = \frac{x_m}{x_{cu}} + \beta \frac{E_h}{F_y x_{cu}} \]  \hspace{1cm} (1)

In which \( D \)=damage index; \( x_m \)=maximum deformation under earthquake; \( x_{cu} \)=failure deformation under monotonic loading test; \( F_y \)=calculated yield shearing strength; \( E_h \)=accumulated hysteretic energy dissipation in loading cycle; \( \beta \)= energy dissipation factor.

A damage index ratio \( D_M \) is defined for damage analysis and it is calculated accorded Eq.2.

\[ D_M = \frac{D_t}{D_T} \]  \hspace{1cm} (2)

In which, \( D_t \) and \( D_T \) are the damage index at time of lateral loading test arrived at t and time of test arrived at failure criterion. In the special loading regulation of this paper, \( D_M \) was decided by maximum lateral displacement \( f_L \) during lateral loading test. The \( D_M f_L \) relationship can be gained with regression analysis, as shown in Eq.3 and Eq.4.

For CFRP retrofitted columns:

\[ D_M = -0.01 + 0.075 f_L + 0.006 f_L^2 \]  \hspace{1cm} (3)

For GFRP retrofitted columns:

\[ D_M = -0.02 + 0.08 f_L + 0.003 f_L^2 \]  \hspace{1cm} (4)

3.3 Immediate Strain of Damaged Column under Axial Loading

Test data and analytical values of axial strains immediately after reapplying the axial load to the damaged column are shown in Table 2. Strain of \( \varepsilon_{ia} \) is the immediate axial strain increment of re-loading. In Table 2, strain of \( \varepsilon_{ia} \) represents the calculated strain value for a given axial stress based on the FRP confined concrete model suggested by Xiao and Wu (2000, 2004). The relationship between \( \varepsilon_{ia} \) and \( \varepsilon'_{ia} \) can be expressed as:

\[ \varepsilon_{ia} = \alpha \varepsilon'_{ia} \]  \hspace{1cm} (5)
In which, $\alpha$ is adjustment factor and which is adopted for convenience in this paper to express the difference between the axial loading strains of the damaged and that of undamaged columns. In other words, $\alpha$ represented a kind of damage index.

**Table 2** Immediate strains of damaged columns under axial loading

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$\varepsilon_{ir}(10^{-6})$</th>
<th>$\varepsilon_{ia}(10^{-6})$</th>
<th>$\varepsilon_{ia}'(10^{-6})$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA-2L</td>
<td>442</td>
<td>869</td>
<td>219</td>
<td>3.97</td>
</tr>
<tr>
<td>CCR-2L</td>
<td>203</td>
<td>383</td>
<td>233</td>
<td>1.64</td>
</tr>
<tr>
<td>CCR-3L</td>
<td>226</td>
<td>459</td>
<td>225</td>
<td>2.04</td>
</tr>
<tr>
<td>CGR-2L</td>
<td>214</td>
<td>442</td>
<td>219</td>
<td>2.02</td>
</tr>
<tr>
<td>CGR-3L</td>
<td>257</td>
<td>523</td>
<td>236</td>
<td>2.22</td>
</tr>
</tbody>
</table>

Note: $\varepsilon_{ir}$: initial radial strain; $\varepsilon_{ia}$: initial axial strain; $\varepsilon_{ia}'$: calculated initial axial strain based on FRP confined concrete model; $\alpha$: adjustment factor, $\alpha=\varepsilon_{ia}/\varepsilon_{ia}'$

In Table 2, it is clear displayed that $\alpha$ is sensitive to the damage degree and the retrofitted material. So a retrofitted effect factor $k$ is defined, as presented in Eq.6.

$$k = \frac{N_r}{N_0}$$  \hspace{1cm} (6)

In which, $N_0$ and $N_r$ are axial loading capacity without FRP retrofitted and axial loading capacity with FRP retrofitted respectively. And $N_r$ is calculated by Xiao-Wu confined concrete model (2000). The influence of retrofitted material and confined degree are both considered in Eq.6. The regression analysis formula between $D_M/k$ and $\alpha$ is listed in Eq.7 and the regression analysis curve is also shown in Fig.4.

$$\alpha = 1 + 1.32(D_M/k) + 4.64(D_M/k)^2$$ \hspace{1cm} (7)

### 3.4 Circumferential Deformation under Post-damage Long-term Loading

After being subjected to pseudo-static test, most lateral deformation of concrete is unrecoverable. So the residual strain of FRP after pseudo-static test is much higher than the initial strain caused by axial load. It means that the concrete in the confined core zone is confined obviously by residual strain of FRP even at the beginning stage of long-term test and it will show the important influence on the creep behaviour of concrete.

![Figure-4 Relationship between DM/k and Adjusted Strain](image)

In the paper, the circumferential residual strain is defined as strain value of FRP jacket after retrofitted columns subjected one time or several times lateral loading cycles, in which $f_L=0$. Similar to analysis method of axial immediate strain, the relationship between circumferential residual strain $\varepsilon_{r,t}$ and its theoretic value $\varepsilon_{r,r}$ is displayed in Eq.8.

$$\varepsilon_{r,r} = \eta \varepsilon_{r,t}$$ \hspace{1cm} (8)
In which, $\eta$ is an adjustment factor of circumferential residual strain. $\eta$ and $D_M$ show the closely relationship and the calculation formulas are presented in Eq.9 and Eq.10.

For CFRP retrofitted columns:  
$$\eta = 0.84 + 30.72D_M + 83.80D_M^2 \quad (9)$$

For GFRP retrofitted columns:  
$$\eta = 2.37 + 35.44D_M + 97.77D_M^2 \quad (10)$$

4. Creep Analysis of Damaged Columns

4.1 Analytical Modeling of Creep

The damaged zone at the end of the column is a hybrid system which is composed of concrete, FRP and steel bars. Three types of material show different creep behaviour and stress redistribution will occur during the long-term loading test.

Selecting creep calculation model of concrete is the first important research foundation in creep analysis. Creep of concrete consists of basic creep and drying shrinkage. Neville (1970) and Russel (1977) showed that drying creep does not exist in wet fresh concrete, drying old concrete and sealed concrete. The concrete in the retrofitted zone wrapped with several layers of FRP coat and can be seen as an ideal sealed concrete. So the main creep of damaged column in retrofitted zone is caused by basic creep. Age adjusted effective modulus method (AEMM) presented by Trost and Bazant (1976) can be applied for calculating basic creep of sealed concrete, as shown in following:

$$\varepsilon(t) = \frac{\sigma(t_0)}{E(t_0)} \left[ 1 + \rho(t, t_0) \right] + \frac{\sigma(t) - \sigma(t_0)}{E(t_0)} \left[ 1 + x(t, t_0) \rho(t, t_0) \right]$$  \hspace{1cm} (11)

Where $t=$ target time; $t_0=$ age at loading; $E(t_0)=$ initial elastic modulus at $t_0$; $\sigma(t)=$stress at $t$; $\rho(t, t_0)=$creep coefficient; $x(t, t_0)=$aging coefficient; $R(t, t_0)=$relaxation coefficient.

FRP is a kind of composite material, in which fiber is strengthening phase and resin is matrix. Glass fiber or carbon fiber do not show creep behaviour but it occur creep in FRP due to the fiber straightening. Resin is a typical of visco-elastic material which can present obviously creep carrying sustained load. So creep resource of FRP includes fiber straightening and resin creep. A simple power law relationship for simulating creep of FRP was suggested by Findley (1960), as displayed in Eq.12.

$$\varepsilon = \varepsilon_0' + \varepsilon_1't^n$$  \hspace{1cm} (12)

In which, $\varepsilon_0'$ is initial elastic strain related to stress-dependent and time-independent; $\varepsilon_1'$ is creep coefficient related to stress-dependent and time-dependent; $t$ is duration time after loading (in hours); $n$ is dimensionless material constant.

4.2 Basic Hypotheses for Creep Calculation

In the hybrid system zone, the axial load is carried by concrete and longitudinal steel bars and the FRP jacket is only sustained confine stress at hoop direction. There are several hypotheses in creep analysis of damaged retrofitted columns at the end of roof zone, as following:

(1) FRP jacket can not carry any axial load. All the axial loads are sustained by concrete and longitudinal steel bars.

(2) The concrete in the confined zone can be seen as a sealed concrete without any moisture released from concrete and the drying creep can be neglected in creep analyzing.

(3) Under the axial loading condition, the hybrid system is consistent with the plane-section
assumption that any normal of a same plane section parallel to each other even after this plane section deformed.

(4) The tensile strain in FRP jacket is equal to the circumferential strain in concrete. So there is no any gap developed between FRP jacket and concrete column.

Creep analysis in the hybrid system zone of retrofitted column also should meet two conditions during whole process of creep calculation, as following:

(1) Static equilibrium: The axial load in concrete added in longitudinal steel bars should be equal to the axial force and the tension in FRP jacket should be equal to lateral pressure in concrete.

(2) Geometric compatibility: Along longitudinal orientation, axial strain in concrete must be equal to strain in longitudinal steel bars. The hoop strain in the wrap must be equal to radial strain in concrete.

4.3 Multiaxial Stress State and Stress Redistribution in Hybrid System

Creep strain of concrete under multiaxial stress condition is less than creep development under uniaxial stress condition. The residual tension in FRP jacket provided obviously confined effect on concrete and made concrete under triaxial compressive stress state even at the beginning stage of long-term loading test. So the creep predicting results by AEMM need to be adjusted according to the multiaxial stress state. Jordaan (1971) stated that the creep strain, under multiaxial stress state, in one direction can be computed using the principle of superposition and presented a creep formula which was similar to those for elastic deformation calculation, as following.

\[
\varepsilon_{E,i} = \frac{E}{\sigma} \left[ \varepsilon_{i} - \nu_{E,i} \left( \sigma_{j} + \sigma_{k} \right) \right]
\]

Where \( \varepsilon_{E,i} \) is the creep strain in the \( i \) direction of the principal stress, \( \nu_{E,i} \) is the effective creep Poisson’s ratio under uniaxial compression in the \( i \) direction, \( \varepsilon \) and \( \sigma \) are the uniaxial creep strain and stress respectively, \( \sigma_{i}, \sigma_{j} \) and \( \sigma_{k} \) are the principal stresses in the \( i, j \) and \( k \) directions respectively.

Due to the difference of material properties, steel bar can be treated as ideal elastic material without any creep, but concrete is visco-elastic material showed obviously creep behavior. So the internal stresses in the hybrid system will vary over time even if the external loads are sustained at a constant level. The stress redistribution will lead to the stress in longitudinal steel bars increasing and the stress in concrete decreasing over time. Therefore, the creep calculation method based on constant stress criteria must be modified to allow for variable stress. The Boltzman principle of superposition can be applied to deal with varying stress situation, as shown in Eq.14.

\[
\varepsilon(t) = \int_{t_0}^{t} \rho(t,t_0)d\sigma(t)
\]

The integration in Eq.14 can be made by a numerical step-by-step procedure as the stress varies over time.

4.4 Creep calculation procedure

Based on the above discussion, a creep calculation method of damaged column was presented. This calculation procedure includes two stages as following:
(1) The static strains and stresses analysis. Firstly, the damage index $D_M$ is calculated by using Eq.3 and Eq.4 according type of FRP and lateral drift ratio. Secondly, the initial axial strain $\varepsilon_{ia}$ in hybrid system is confirmed with Eq.5 to Eq.7 when applied long-term load. Thirdly, the residual strain in FRP jacket $\varepsilon_{rr}$ is decided by Eq.8 to Eq.10. Finally, a load factor $\alpha$ is used to estimate the axial load distribution in concrete $P_c$ and in longitudinal steel bars $P_s$, as shown in Eq.15 and Eq.16. Then the initial stress in concrete can be confirmed.

\begin{align*}
P_c &= \alpha P \\
P_s &= P - P_c
\end{align*}

At the initial of applied long-term loading, $\alpha$ is estimated based on the stiffness ratio of the section, as following:

\begin{equation}
\alpha = \frac{E_c A_c}{E_c A_c + E_s A_s}
\end{equation}

In which, $E_c$ and $E_s$ are elastic modulus of concrete and steel bar respectively. $A_c$ and $A_s$ are sectional areas of concrete and steel bar respectively.

(2) Algorithm of creep calculation. Firstly, increasing time step of $\Delta t$ and using AEMM calculate the uniaxial creep strain increment $\Delta \varepsilon_{ca}$ of concrete under initial stress level. Secondly, $\Delta \varepsilon_{ca}$ is modified according to the triaxial stress state with Eq.13 and the radial creep increment of concrete is gained by $\nu_{EPR} \times \Delta \varepsilon_{ca}$. Thirdly, using Findley’s power law and Boltzman superposition principle find the creep strain of FRP jacket under the current tensile stress level. Lastly, check lateral strain compatibility between circumferential strain in concrete and hoop strain in FRP jacket. If the difference is greater than the preset tolerance, adjust the hoop strain in FRP jacket and calculate the new lateral confined stress and repeat calculating $\Delta \varepsilon_{ca}$ according to the triaxial stress state until meeting the condition of lateral strain compatibility. Then for a next time step $\Delta t$, axial stresses in concrete and in steel bars is updated due to stress redistribution. The algorithm is repeated for the duration of long-term loading test.

![Figure-5 Creep strain of test compared with calculation](image)

Because of without any data about creep of damaged retrofitted column gained, the above creep model is verified against test results in this paper. Fig.5a and Fig.5b show the creep model predictions compared with creep data of the test column CA-L and CCR-3L respectively. Good agreement is noted for both two specimens.
5. Conclusions

(1) During long-term axial loading test after being subjected to some degree of lateral loading damage, the deformation of the FRP retrofitted columns was lower when compared with the non-retrofitted column subjected to similar loading condition.

(2) The creep behavior of retrofitted column was found to be controlled by damage level and related to the modulus of elasticity of the FRP.

(3) The study essentially confirmed that within the testing range of the axial load ratios between $0.2 - 0.4\frac{Agfc'}{f'c}$, the post damage long-term axial loading would not cause any significant creep effects to the FRP retrofitted columns.

(4) A creep analysis model was presented which considered the effects of sealed concrete, multi-axial state of stresses, creep Poisson’s ratio, stress re-distribution, variable creep stress history, damaged degree of earthquake and creep rupture of column. The creep model was verified against creep test for FRP confined concrete and long-term test in this paper. It shows acceptable agreement between prediction and test data.

References


