Seismic damage pattern analysis of high piers of RC bridges based on the fiber model

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Abstract. The practical method of the seismic damage analysis of high piers of RC bridges is established using the uniaxial modified Faria-Oliver damage model for concrete and modified Menegotto-Pinto model for rebars, based on the fiber beam-column element, in the FEA software ABAQUS. Furthermore, the seismic damage analysis of short pier and high piers of different section sizes are conducted, respectively. The results indicate that for the short piers the damage zone is located at the bottom of piers. However, the high piers tend to have multi-location damage zones, and the tendency is more obvious for the high piers with a more slender shape.

1. Introduction

In recent years, China's transportation infrastructure construction is developed rapidly, and a large number of highway and railway bridges with the high piers which are usually over 40m high are built in the mountainous area of Western China. Some researchers studied the seismic performance of the high-pier bridges through different models and methods. For example, Liang and Li studied the reasonable modelling method based on the plastic hinge beam-column element and the fiber beam-column element, respectively [1]. Xia, Chen et al. conducted the seismic analysis of the high piers using the Takeda hysteretic model [2]. Li, Song et al. evaluated the displacement ductility performance using the IDA [3]. He, Tian et al. combined the rigid element and the rotational spring element for modelling the plastic hinge behavior, in the FEA software ANSYS [4], then based on the modelling strategy, a seismic analysis of a continuous rigid frame bridge with high piers and long spans was carried out. Based on the solid element in the FEA software LS-DYNA, Sun, You et al. stimulate the collapse process of the RC high pier bridge [5]. Zhang, Han et al. developed a fiber beam element subroutine in the software MSC.MARC, and evaluated the influence of traveling wave on the nonlinear seismic response of a continuous rigid frame bridge with high piers [6]. Li performed a seismic analysis of a RC bridge with high piers considering the strain rate effect of the concrete using ABAQUS [7].

The solid element model is a more refined method with high computational cost. Therefore, the usage of this model is not common. The beam-column element model includes the plastic hinge model and the fiber model and is the main method in the practical engineering. Compared to the plastic hinge model, the fiber model has higher accuracy and lower computational cost. Consequently, the fiber model becomes widely used nowadays.

In the present study, the uniaxial constitutive model for concrete is introduced in the fiber model taking into account the compressive and tensile damage. Thus the damage process of the RC bridge pier under the earthquake can be stimulated naturally by the fiber mode. A uniaxial version is derived from the 3D Faria-Oliver elastoplastic damage model for the concrete [8]. In addition, a modification is
proposed for a more reasonable depict of unilateral behavior of the concrete. And then in the platform of the FEA software ABAQUS/Explicit, the subroutine VUMAT is implemented based on the modified uniaxial Faria-Oliver damage model for the concrete and the modified Menegotto-Pinto model for the rebars [9,10]. The seismic damage analyses of the high pier and the short one are performed and the characteristic of the seismic damage of high piers with different section sizes are discussed as well.

2. Uniaxial constitutive models

2.1 Modified uniaxial Faria-Oliver damage model for concrete

The equivalent effective tensile and compressive stresses are defined as, respectively:

\[
\tau^+ = \left| \sigma^+ \right| \sqrt{E_0^{-1}}
\]

\[
\tau^- = \sqrt{\frac{1}{3} \left( K \sigma^- + \sqrt{3} \left| \sigma^- \right| \right)}
\]

where, \( E_0 \) is the elastic modulus; \( \sigma^+, \sigma^- \) is the tensile and compressive effective stresses, respectively; \( K \) is a parameter.

The evolution equations of the tensile and compressive damages are as follows, respectively:

\[
d^+ = 1 - \frac{d^+}{\tau^+} e^{\frac{\left| \sigma^+ \right|}{\tau^+}}
\]

\[
d^- = 1 - \frac{d^-}{\tau^-} \left( 1 - A^- \right) - A^- e^{\frac{\left| \sigma^- \right|}{\tau^-}}
\]

where, \( d^+, d^- \) are the initial values of the tensile and compressive damage thresholds, respectively; \( A^-, B^- \) are the model parameters.

The evolution equation of the plastic strain \( \varepsilon^p \) is:

\[
\dot{\varepsilon}^p = -\beta E_0 H \left( d^- \right) \left( -\dot{\varepsilon} \right) E_0^{-1}
\]

where, \( \beta \) is parameter related to the plasticity, \( H(\cdot) \) is Heaviside function.

The effective tensile and compressive stresses are as follows:

\[
\sigma^+ = E_0 \varepsilon^+
\]

\[
\sigma^- = E_0 \left( \varepsilon^- - \varepsilon^p \right)
\]

where, \( \varepsilon^+, \varepsilon^- \) are tensile and compressive strains, respectively.

The stiffness influence factor \( s \) is introduced, in order to consider the unilateral effect of the concrete under the cyclic loading properly. The expression of the modified total stress \( \sigma \) is as follows:

\[
\sigma = (1 - s \sigma^-)(1 - \sigma^+) + (1 - \sigma^-)\sigma^-
\]

with the factor \( s \) defined as:

\[
s = \begin{cases} 0 & \sigma = 0 \\ 0 & \sigma = 0 \\ s_0 & \sigma \neq 0 \end{cases}
\]

where, \( \langle \cdot \rangle \) is Macaulay bracket; \( s_0 \) is calibrated by the experiment, the range of the value is \([0,1]\).

The cyclic stress-strain curves of the modified damage model and the original model are plotted together in Figure 1. The influence of the compressive damage on the tensile stiffness of the modified model is shown in Figure 1.
Figure 1. Curve of stress-strain of the modified uniaxial Faria-Oliver model

The effect of the confined concrete (i.e. the enhancement of the strength and the ductility) is implemented by adjusting the parameters $A^-$ and $B^-$. The specific method herein is cited from the Kent-Park model.

2.2 Modified Menegotto-Pinto model for rebar

The Menegotto-Pinto model is a classical model for rebar [9]. The expression is as follows:

$$
\sigma^* = b\varepsilon^* + \frac{(1-b)\varepsilon^*}{(1+\varepsilon^* R)^{1/R}}
$$

Where, $\varepsilon^* = (\varepsilon - \varepsilon_r)/(\varepsilon_0 - \varepsilon_r)$, $\sigma^* = (\sigma - \sigma_r)/(\sigma_0 - \sigma_r)$, $b = E_i / E_r$, $R = R_0 - a_1\xi / (a_2 + \xi)$, $\xi = (\varepsilon_m - \varepsilon_0)/\varepsilon_r$, $(\varepsilon_r, \sigma_r)$ is the strain reversal point, $(\varepsilon_0, \sigma_0)$ is the intersection of the elastic asymptote and the yield asymptote, $\varepsilon_m$ is the maximum or the minimum of the strain, $b$ is the ratio of the hardening modulus and the elastic modulus, $R$ is a parameter related to the Bauschinger effect. However, the model has the shortcoming that in the process of partial unloading and reloading, the stress and the stiffness become too big. In view of that, Sakai and Kawashima make a modification to the model [10]. The expressions are introduced as follows:

$$
\sigma = \begin{cases} 
\sigma_{s1} & \sigma_{s1} \leq \sigma_p \\
\sigma_p & \sigma_{s1} > \sigma_p 
\end{cases} \quad \text{(strain increases)} \quad (11)
$$

$$
\sigma = \begin{cases} 
\sigma_{s1} & \sigma_{s1} \geq \sigma_p \\
\sigma_p & \sigma_{s1} < \sigma_p 
\end{cases} \quad \text{(strain decreases)} \quad (12)
$$

where, $\sigma_{s1}$ is the stress in the loading path started from the previous strain reversal point, $\sigma_p$ is the stress in the path of partial unloading and reloading. The difference between the modified version and the original version is shown in Figure 2. So the modified model seems to make up for the shortcoming properly.

Figure 2. Curve of stress-strain of the modified Menegotto-Pinto model
2.3 Implementation of the fiber model in ABAQUS

The modified uniaxial Faria-Oliver damage model for concrete and the modified Menegotto-Pinto model by Sakai-Kawashima are implemented in the ABAQUS using Fortran as an user material subroutine VUMAT. Three types of material models are contained in the VUMAT: the confined concrete, the unconfined concrete and the rebars. The algorithm is the same between the confined concrete and the unconfined concrete, except the model parameters. Then the seismic damage analysis of the RC bridge piers is available based on the fiber beam-column elements.

3. Seismic damage pattern analysis of the high piers

3.1 Analysis models

Two typical high piers with different size of section and a regular (short) pier are analyzed. The height of the high piers are both 90m; the short one is 30m high. The cross sections of the piers are the box. The dimensions of the sections of the high piers are shown in Figure 3(a), 3(b), and the short one is shown in Figure 3(c). The thickness of the concrete cover of the section is 4cm, the reinforcement ratio is 1.4%, and the equivalent lumped mass on the top of the pier is 760t. The material parameters are listed in Table 1. The analysis models are shown in Figure 4. The uniaxial modified Faria-Oliver damage model for the concrete and modified Menegotto-Pinto model for rebars are applied. The bottom of the piers is fixed. The ABAQUS/Explicit is the FEA solver.

![Diagram of piers](image)

Figure 3. Dimensions of the section of the piers (unit:cm)

| Material | Elastic modulus (GPa) | Compressive strength (MPa) | Tensile strength (MPa) |
|----------|-----------------------|---------------------------|-----------------------|
| Concrete | 31                    | 30                        | 3                     |
| Rebar    | 210                   | 335                       | 335                   |

Table 1. Material properties of the RC bridge piers
In order to evaluate the characteristic of damage of the high piers with the different sectional dimensions, the damage process of the piers under five seismic waves are stimulated. The input earthquake recorders are listed in Table 2. The amplitudes of seismic waves are scaled to 0.3g uniformly. The predominant period ranges from 0.26s to 1.22s.

**Table 2. Earthquake recorders**

| Earthquake recorder | Predominant period (s) | Average period (s) | Duration (s) |
|---------------------|------------------------|--------------------|--------------|
| El-Centro wave      | 0.460                  | 0.529              | 40           |
| Taft wave           | 0.360                  | 0.538              | 54.36        |
| Northridge wave     | 0.260                  | 0.534              | 40           |
| Kobe wave           | 1.220                  | 1.092              | 30           |
| Tianjin wave        | 0.940                  | 0.871              | 19.19        |
3.2 Results and discussion

The damage value of each fiber can be obtained in the analysis. The damage diagram of the typical fiber of concrete is selected as a representative for describing the damage distribution of the whole RC pier.

As for the short pier, the damage pattern is not sensitive to the input seismic waves. Basically, the damage zone occurs in the bottom of the piers, and then gradually expands upward along the pier, as shown in Figure 5. Nevertheless, as for the high piers, because of the influence of the high order modes, the damage of the high piers tends to occur in multiple locations of the piers, as shown in Figures 6(a), 6(b), 7(b). However, the tendency of the multi-location damage of the high pier with the smaller section (i.e. the slender one) is more obvious. In fact, the high pier with the bigger section occurs multi-location damage just under certain earthquakes as shown in Figure 6(a), whereas under other earthquake, the phenomenon does not exist. In this case, the damage pattern is similar with the short pier, as shown in Figure 7(a).

![Damage evolution of the short pier under El-Centro wave](image1)

![Damage evolution of the high pier 1](image2)

Figure 5. Damage evolution of the short pier under El-Centro wave

(a) High pier 1
Figure 6. Damage evolution of the high pier under El-Centro wave
Figure 7. Damage evolution of the high pier under Kobe wave

4. Conclusions
The damage pattern of the short pier is very stable when subjected to the earthquakes, that is, the damage concentrated in the bottom zone of the pier.

In the other hand, the damage pattern of the high piers is sensitive to the input seismic waves. Due to the high order modes, the damage zone often arises in multiple locations in the pier body. The process and zone of the damage of the high pier is more complex than the short pier. The multi-location damage pattern of the high pier which is more slender occurs more easily.

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