VERIFICATION OF A REINFORCED CONCRETE COLUMN COMPUTER MODEL UNDER UNIAXIAL AND BIAXIAL BENDING LOADING CONDITIONS

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ABSTRACT

Nowadays, computer has become an important tool to support researchers in performing structural analysis in the field of structural engineering. Many computer models have been developed by researchers in the past few decades to simulate the real structural behavior. These models range from the simplest one to the most sophisticated one, each with its own advantages and disadvantages. One of the most recent models of reinforced concrete (RC) column is fiber model. This study aims to check the ability of a fiber model that once was developed to simulate RC column hysteretic behavior under uniaxial and biaxial bending loading conditions. This is done to ensure the validity of the fiber model to be used in three-dimensional nonlinear dynamic time history analysis as it is one of the most advanced methods nowadays to perform seismic performance evaluation. A real experimental testing of RC columns hysteretic behavior under uniaxial and biaxial bending loading was taken to be the reference. In this study, the computer platform used is OpenSees, a numerical simulation software developed by Pacific Earthquake Engineering Research Center (PEER) which provides its users high flexibility to define models, materials behavior as well as the loading patterns. Later, the computer analysis results of the fiber model are compared with the reference experimental results. The comparisons between them show that the fiber model with proper assumptions of the model parameters can simulate quite well the hysteretic behavior of RC column under uniaxial and biaxial bending loading.

Keywords: fiber model, RC column, hysteretic behavior, uniaxial and biaxial bending loading

1. INTRODUCTION

Nowadays, computer has become an important tool that helps researchers as well as practicing engineers in performing structural analysis in the field of structural engineering. As it is no longer practical to do the analysis by hand as it is used to be in the past, thus the use of computer as a tool has become increasingly significant. Furthermore, rapid technology development has made computer a super machine which is able to perform structural analysis with great speed as well as good accuracy. These great speed and good accuracy seem impossible for human to achieve if the analysis is done by hand. Therefore, structural engineers can hardly avoid the use of computer in helping them performing structural analysis, especially for complex structures. However, even with its superiorities, computer is still a machine that works based on the orders inputted. If the input is not correct, then the output will also be wrong. In other words, engineers and researchers should make sure that the input is correct in order to get good results as expected. In this case, the step of modelling real structure into computer model in which computer cannot replace engineers plays important roles that will determine the analysis results.

Many computer models have been developed by researchers in the past few decades to simulate the real structural behaviour. These models range from the simplest one to the most sophisticated one, each with its own advantages and disadvantages. For example, modelling of a beam can be done in many ways. The simplest one is spine model (1D), which the beam is modelled as a single line with its properties. The more complicated one is shell model (2D), which the beam is modelled by a set of shell elements connected together to form a beam. The last one which is the most sophisticated one is solid model (3D), which the beam is modelled by a set of solid elements connected together to form a beam. In fact, since each model has its own benefits as well as limitations, hence engineers should carefully determine which model should be used for a specific problem.

Modelling of reinforced concrete (RC) column for nonlinear dynamic analysis has been a challenge for researchers in the past few decades. Unlike steel, RC has more complicated properties which make it complex to take into account all possible behaviours such as steel reinforcements yielding, concrete crushing, concrete spalling, lap-slice failure, shear failure, etc. One of the most recent models of RC column is fiber model. This model is based on the idea that a cross section of a RC column is divided into many layers which consist of cover concrete layers, core concrete layers, and steel reinforcement layers. Each layer has its own material properties which make it possible to model different material behaviour between cover concrete, core concrete, and steel reinforcement. Thus, it is an
advantage of fiber model as compared to other models in which concrete and steel layers may not be modelled separately. Another advantage is the fiber model can take into account variations in RC column axial loads during nonlinear dynamic time history analysis. This is an important feature since the capacity of the column itself depends on the axial loads that happened in the column. In addition, fiber model can combine the moment capacity of the column in many different angles which make it favourable to be used in three-dimensional analysis.

This paper presents a case study of verification of a RC column fiber model that was developed by Suthasit (2007) under uniaxial and biaxial bending loading conditions. This study aims to check the ability of the model to simulate RC column hysteretic behavior under those loading conditions. This is done to ensure the validity of the fiber model to be used in three-dimensional nonlinear dynamic time history analysis as it is one of the most advanced methods nowadays to perform seismic performance evaluation. A real experimental testing of RC columns hysteretic behavior under uniaxial and biaxial bending loading done by Qiu et al. (2002) was taken to be the reference.

2. RC COLUMN FIBER MODEL

The computer model that is verified in this paper is a RC column fiber model developed by Suthasit (2007). The two dimensional architecture of the model can be seen in Figure 1. The model mainly comprises three sub components which are a pair of zero length fiber section elements, a linear elastic frame element, and a pair of shear springs. Furthermore, in order to take into account the flexural deformation in stiffness computation, the concentrated plasticity approach is adopted in this model. It is assumed that nonlinearity due to flexural deformation can only occur at both ends of the column. Thus, a series of two zero length fiber section elements and a linear elastic frame element are used to model the flexural deformation of the column.

![Figure 1. RC column fiber model developed by Suthasit (2007)](image)

In this model, the zero length fiber section element is divided into several layers, which are cover concrete layers (unconfined), core concrete layers (confined), and steel reinforcement layers. Each layer is modelled separately using uniaxial nonlinear springs with different material properties which simulate the nonlinear behaviour of concrete and steel. It should be noted that the basic assumption in this model is plane section remains plane.
Moreover, the equivalent plastic hinge length concept proposed by Paulay and Priestley (1992) is adopted in this model.

To simulate the axial and flexural stiffness in the middle part of the column where it is assumed that there is no nonlinearity, a linear elastic frame element is used. Nevertheless, since cracked sections always exist in a RC column member, thus axial and flexural stiffness of the column would not be the same as the gross section stiffness. The effective axial and flexural stiffness values recommended by ASCE Standard for Seismic Rehabilitation of Existing Buildings (ASCE/SEI 41-06) (ASCE, 2007) were used in this study, which are 1.0 times of gross section stiffness for axial stiffness and 0.5 times of gross section stiffness for flexural stiffness.

The shear springs are used to simulate shear failure in the RC column. Nonetheless, since in this study the focus is on the flexural capacity of the column, hence the shear capacity would not be discussed in detail.

3. REAL EXPERIMENTAL TESTING OF RC COLUMNS SUBJECTED TO UNIAXIAL AND BIAXIAL BENDING LOADING CONDITIONS

A real experimental testing of RC columns hysteretic behavior under uniaxial and biaxial bending loading conditions done by Qiu et al. (2002) was taken to be the reference in this study. The experiment itself was intended to compare the deformability and character of damaged columns under uniaxial and biaxial bending loading. Furthermore, the status of hysteresis energy dissipation and accumulative damage of different columns were also be investigated. In this experiment, quasi-static test method and displacement control mode were used as the loading method. Details about the specimens tested and load paths used can be seen in Figure 2 and 3, respectively. In this study, however, the verification of the RC column fiber model has been done only for the first three specimens (i.e., RC-0, RC-1, and RC-2).

![Figure 2. Details of specimens tested by Qiu et al. (2002)](image)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>RC-0</th>
<th>RC-1</th>
<th>RC-2</th>
<th>RC-3</th>
<th>RC-4</th>
<th>RC-5</th>
<th>RC-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load path</td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
</tr>
<tr>
<td>$f_c$ (N/mm²)</td>
<td>39.6</td>
<td>40.9</td>
<td>37.7</td>
<td>37.5</td>
<td>38.9</td>
<td>38.2</td>
<td>34.8</td>
</tr>
<tr>
<td>Axial load N (kN)</td>
<td>350</td>
<td>350</td>
<td>350</td>
<td>350</td>
<td>350</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>$N/Af_c$</td>
<td>0.228</td>
<td>0.210</td>
<td>0.228</td>
<td>0.229</td>
<td>0.221</td>
<td>0.230</td>
<td>0.211</td>
</tr>
</tbody>
</table>

![Figure 3. Loading paths and parameters of the specimens (Qiu et al., 2002)](image)
4. MODELLING OF RC COLUMNS

In this study, the computer platform used is OpenSees, a numerical simulation software developed by Pacific Earthquake Engineering Research Center (PEER) which provides its users high flexibility to define models, materials behaviour as well as the loading patterns. The open source approach of OpenSees gives many benefits for its users who are interested in advanced simulation of structural systems to add additional features or capabilities. Furthermore, OpenSees as a powerful tool for numerical simulation of nonlinear systems provides huge number of materials which are very useful for nonlinear analysis.

The first three specimens (RC-0, RC-1, and RC-2) in Qiu et al. (2002) experiment are modeled in OpenSees using RC column fiber model developed by Suthasit (2007). The RC columns are modeled as cantilever columns with fixed base. The zero length fiber section element and the nonlinear shear spring are put at the fixed end of the columns while the linear elastic frame element connects the fixed end and the free end of the columns. The loading patterns follow the load paths as defined in Qiu et al. (2002) experiment and the displacement control mode is used for the loading method.

As one of the advantages of fiber model is concrete and steel layers can be modelled separately using different material behaviour, thus the zero length fiber section element is discretized as shown in Figure 4. The cross section of the RC columns is divided into many segments in which each segment is represented by one uniaxial nonlinear spring which simulates the nonlinear behavior of either cover concrete (unconfined) or core concrete (confined) or steel reinforcement. Later on, these uniaxial nonlinear springs are connected together to the master node using rigid links. By default, OpenSees provides many types of nonlinear material behavior of concrete and steel. In this study, Concrete02 Material and Steel02 Material have been chosen to simulate nonlinear behavior of concrete and steel reinforcement. The example of hysteretic behavior of these materials can be seen in Figure 5.

![Discretization of cross section of RC columns](image1)

![Example of hysteretic behavior of Concrete02 Material and Steel02 Material in OpenSees](image2)
Another important aspect that should be considered is the modelling of confinement effect in core concrete. This confinement effect provided by stirrups increases core concrete strength and ductility as compared to cover concrete where there is no confinement effect by stirrups. Suthasit (2007) recommended equations given by Mander et al. (1988) to calculate the peak compressive strength and the associated strain of the confined core concrete. These equations are displayed as follows.

\[ f'_{cc} = K f'_{co} \]  

In which:

- \( f'_{cc} \) = compressive strength of confined concrete (MPa)
- \( f'_{co} \) = compressive strength of unconfined concrete (MPa)
- \( K \) = confined strength ratio which is a function of lateral reinforcement configuration, strength and amount of lateral reinforcement and longitudinal reinforcement, and section dimensions (detailed description can be found in Mander et al. (1988))

\[ \varepsilon_{cc} = \varepsilon_{co} \left[ 1 + 5 \left( \frac{f'_{cc}}{f'_{co}} - 1 \right) \right] \]  

In which:

- \( \varepsilon_{cc} \) = strain at peak compressive strength of confined concrete
- \( \varepsilon_{co} \) = strain at peak compressive strength of unconfined concrete

The final analytical model of the RC columns is displayed in Figure 6.

5. **ANALYSIS RESULTS**

Analysis results of the three specimens (RC-0, RC-1, and RC-2) are presented in terms of force-displacement relationship of the top free end node. For RC-0 specimen, since it is subjected to uniaxial bending loading, thus the responses recorded are only in one direction (x-axis only) whereas for RC-1 and RC-2 specimens, the responses are recorded in two directions (x-axis and y-axis) since they are subjected to biaxial bending loading. Furthermore, these analysis results of the three specimens are compared with real experimental results done by Qiu et al. (2002) in order to see how the RC column fiber model developed by Suthasit (2007) can simulate the hysteretic behaviour of RC columns under uniaxial and biaxial bending loading conditions. The complete analysis results as well as comparisons with real experimental results can be seen in following figures.
RC-0

Figure 7. Comparison of force-displacement relationship between experimental result (left) tested by Qiu et al. (2002) and analytical result (right) of RC-0 specimen

RC-1

Figure 8. Comparison of force-displacement relationship between experimental result (left) tested by Qiu et al. (2002) and analytical result (right) of RC-1 specimen in x-axis

Figure 9. Comparison of force-displacement relationship between experimental result (left) tested by Qiu et al. (2002) and analytical result (right) of RC-1 specimen in y-axis
6. DISCUSSIONS AND CONCLUSIONS

The comparisons show good agreement between real experimental results and analytical results. The RC column fiber model can predict flexural failure of the RC columns for all cases. Furthermore, the flexural strength and hysteretic behaviour of the RC columns under uniaxial and biaxial bending loading conditions can be well predicted by the model. However, for strength degradation, the model predicts slightly higher strength as compared to the experiment results in all cases. Moreover, the model shows exactly symmetrical hysteretic behavior in positive and negative displacement history whereas the experiment results do not show exactly symmetrical hysteretic behavior. Nevertheless, overall it can still be concluded that the RC column fiber model gives good prediction of the flexural behavior of RC columns under uniaxial and biaxial bending loading conditions. Indeed, this verification ensures the validity of the model to be used in three-dimensional nonlinear dynamic time history analysis as it is one of the most advanced methods nowadays to perform seismic performance evaluation.

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