SEISMIC RESPONSE ANALYSIS OF RC STRUCTURES CONSIDERING STRENGTH DEGRADATION CAUSED BY CYCLIC LOADING

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ABSTRACT:

It is well known that the strength of reinforced concrete columns is degraded by cyclic loading, particularly in the post-peak region. When we examine the seismic safety of RC structures, it is important to conduct the dynamic response analysis considering the strength degradation by cyclic loading. In this study, we first develop a nonlinear dynamic hysteresis model, which can take into account the strength degradation. Secondary, we attempt to evaluate the effects of duration time of earthquake in the post-peak region through seismic response analysis by using the proposed model. As a result, we clarified that the post-peak behavior of reinforced concrete structures varies depending on the duration time of ground motion.

KEYWORDS: cyclic loading, strength degradation, nonlinear hysteresis model

1. INTRODUCTION

It is a common knowledge that the strength of reinforced concrete columns is degraded by cyclic loading, particularly in the post-peak region. A lot of static cyclic loading tests for RC members have been conducted. According to these tests, it has been pointed out that the seismic performance of RC members is affected by cyclic patterns [1]. When we examine the seismic safety of RC structures, it is important to conduct the dynamic response analysis considering the strength degradation by cyclic loading.

Various nonlinear hysteresis models for dynamic response analysis have been ever proposed. Most of these models, for example the Clough model [2] and the Takeda model [3], however, do not consider the effects of strength degradation. Therefore, these models are generally applicable to before-peak region.

In order to evaluate the post-peak behavior of RC structures, we develop a nonlinear hysteresis model that can take into account the strength degradation for dynamic response analysis. Furthermore, we attempt to evaluate the effects of cyclic characteristics of earthquake in the post-peak region by using the proposed model.

2. DEVELOPMENT OF NONLINEAR HYSTERESIS MODEL

2.1 Concept of Strength Degradation

Figure 1 shows the fundamental concept of strength degradation. We represent the strength degradation by moving a previous oriented point $d_p$ at the-(i-1)-step to a new oriented point at the-(i)-step as shown in Fig. 1. We assume that the moving distance $\Delta d$ is closely related to positive and negative reversal points at (i-1) step. The distance $\Delta d$, therefore, is obtained by Eqn. (2.1). In Eqn. (2.1), the parameter $\chi$ represents the strength degradation degree. If the value of $\chi$ is large, a new oriented point moves largely and then the strength decreases more.

\[ d_i = d_p + \Delta d = d_p + (d_{\text{max}} - d_{\text{min}}) \cdot \chi \]  

where,

$\begin{align*}
\chi & : \text{new oriented point} \\
\chi_p & : \text{previous oriented point}
\end{align*}$
The shaking table tests have been ever conducted [5]. According to these experiments, after the amplitude of the response displacement exceeds the twice as much as displacement \( M_d \) of approximately maximum load sustained point, the damage of RC columns becomes sever and there is possibility of collapse [5]. These results mean that the strength is also degrading prominently beyond \( M_d \) in the static cyclic loading test as shown in Fig. 2. Therefore, we divide \( \chi \) into \( \chi_I \) and \( \chi_H \). The parameter \( \chi_I \) is used until the amplitude of displacement exceeds \( 2\delta_M \). The parameter \( \chi_H \) is used beyond \( 2\delta_M \).

2.2 Hysteresis Rules of Newly Developed Model

In this section, we describe the detailed hysteresis rules about the proposed model. Figure 3 shows the example of hysteresis loop. Backbone curve is bilinear.

(i) If the response is below a positive yield point \( Y^+ \), the response traces the line □.
(ii) The response shifts to the positive second slope beyond \( Y^+ \) (line □).
(iii) If unloaded on the positive second slope, the load decreases to zero with unloading stiffness (line □).
(iv) After crossing \( P = 0 \), the response orient the negative yield point \( Y^- \) (line □).
(v) The response traces the negative second slope (line □).
(vi) The same as (iii)
(vii) If the amplitude \( (d_{max} - d_{min}) \) of the previous loop (line □ - □) is less than \( 2\delta_M \), a new oriented point \( d_{nl} \) is calculated by Eqn. (2.1) with the parameter \( \chi_I \) (line □).
Table 1  Properties of Existing Test Pieces

<table>
<thead>
<tr>
<th>Test piece No.</th>
<th>Section size [mm]</th>
<th>Effective depth d [mm]</th>
<th>Shear span a [mm]</th>
<th>a/d</th>
<th>Longitudinal reinforcement 1)</th>
<th>Hoop reinforcement 1)</th>
<th>Axial stress σσ / [% N/mm²]</th>
<th>Tensile reinforcement ratio pσpσ / [%]</th>
<th>Hoop reinforcement ratio pσpσ / [%]</th>
<th>Concrete strength f'c / [N/mm²]</th>
<th>Cyclic pattern 2)</th>
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<tr>
<td>H95-1</td>
<td>900*900</td>
<td>821</td>
<td>3300</td>
<td>4.0</td>
<td>SD345-D32</td>
<td>SD345-D32</td>
<td>1.07</td>
<td>0.28</td>
<td>30.0</td>
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<td>3 times 180°</td>
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<td>28.0</td>
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<td>29.2</td>
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<td>3000</td>
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</table>

*1) SD 345 - D32  □ deformed bar, □ nominal strength, □ nominal diameter
□ □ □
*2) n times / m δ: number of cyclic times per m δ

Fig. 4  Frequency Distribution of Parameter $\chi_1$ Obtained by Static Loading Tests

- (viii) If the response reaches the second slope, traces line □ .
- (ix) The same as (iii)
- (x) The same as (vii)
- (xi) The same as (iii)
- (xii) If the amplitude $(d_{max} - d_{min})$ of the previous loop (line □ - □ ) is greater than $2\delta_M$, a new oriented point $d_{s2}$ is calculated by Eqn. (2.1) with the parameter $\chi_2$ (line □ ).

2.3 Parameter Identification

It has been ever pointed out that the strength degradation degree depends on properties of RC members, such as tensile reinforcement ratio $p_t$ and hoop reinforcement ratio $p_w$ [6]. The proposed model controls the degradation degree by using the parameter $\chi$. Therefore, we attempt to formulate the parameter $\chi$ by using the results of many static cyclic loading tests.
The properties of existing test pieces are shown in Table 1 [7]. The parameter \( \chi_{I, exp} \) and \( \chi_{II, exp} \) obtained from the static loading tests are shown in Fig. 4. As shown in Fig. 4(a), the average and the variation coefficient of \( \chi_{I, exp} \) are very small. Therefore, we regard \( \chi_{I, exp} \) as zero. On the other hand, \( \chi_{II, exp} \) varies considerably depending on properties of RC members. Therefore, we formulate the regression equation among \( \chi_{II, exp} \), \( \rho_t \), and \( \rho_p \). Figure 5 shows the relationship between \( \chi_{II, exp} \) and \( \rho_p \). The parameter \( \chi_{II, exp} \) decreases exponentially with increasing \( \rho_p \). Its regression equation, therefore, can be expressed as follows:

\[
\chi_{II, exp} = 0.54 \cdot e^{-1.3 \rho_p} 
\]  

(2.2)

where \( e \) is exponential function and \( \rho_p \), hoop reinforcement ratio [%]

Secondary, the relationship between \( \chi_{II, exp} / \chi_{II, cal1} \) and \( \rho_t \) is shown in Fig. 6. \( \chi_{II, exp} / \chi_{II, cal1} \) increases linearly with increasing \( \rho_t \). Therefore, the regression equation of the relationship is expressed as follows:

\[
\chi_{II, exp} / \chi_{II, cal1} = 1.06 \cdot \rho_t 
\]  

(2.3)

where \( \rho_t \) is tensile reinforcement ratio [%]

Consequently, the parameter \( \chi_{II} \) is expressed by substituting Eqn. (2.2) into Eqn. (2.3) as follows:

\[
\chi_{II} = 0.57 \cdot \rho_t \cdot e^{-1.3 \rho_p} 
\]  

(2.4)

Figure 7 compares \( \chi_{II} \) with \( \chi_{II, exp} \). The parameter \( \chi_{II} \) is estimated by Eqn. (2.4) and The parameter \( \chi_{II, exp} \) is obtained from the static loading experiments. We can see that the parameter \( \chi_{II} \) agrees well with \( \chi_{II, exp} \). Therefore, the parameter \( \chi_{II} \) can be formulated by Eqn. (2.4) using \( \rho_t \) and \( \rho_p \). In addition, this equation is applicable within the range of properties of RC members shown in Table 1.
3. VERIFICATION OF NEWLY DEVELOPED MODEL

In order to verify our newly model, we simulate the result of the static cyclic loading tests in Table 1. As the examples, the results of H97-6 and H97-1 are shown in Fig. 8 and Fig. 9. (a) indicates the cyclic loading pattern. While (b) expresses the load-displacement relationship.

Paying attention to post-peak region, we see that this model can simulate the strength degradation by cyclic loading at both loading pattern. In addition, we have confirmed that this model can also represent the strength degradation at the other cases in Table 1.

4. SEISMIC RESPONSE ANALYSIS

In this chapter, we conduct the seismic response analysis of the pier, which can be expressed by a single-degree-of-freedom system, in order to evaluate the effects of cyclic characteristics of earthquake. Input ground motions are shown in Fig. 10 [8]. The wave of spectrum I targets near-land interplate earthquakes. The wave of Spectrum II expresses earthquakes produced by inland active faults. The parameters in this analysis are as follows:

1) The yield seismic coefficient of pier is 0.4.
2) The equivalent natural period is 0.8.
3) The parameter \( \chi_i \) is zero and, \( \chi_{II} = 0.15 \).

The results of response analysis are shown in Fig. 11. In Fig. 11(a), the strength is decreased by a lot of cyclic pulses, and then the response displacement becomes large. On the other hand, in Fig. 11(b), the maximum response displacement is determined by a few pluses. The response displacement is, therefore, relatively small. As described above, the dynamic behavior of RC structures differs depending on the duration time of earthquake motion. In order to evaluate the seismic performance, it is necessary to consider the effects of cyclic characteristics of earthquake motions.
5. CONCLUSIONS

In this study, we have developed a nonlinear dynamic hysteresis model for RC members, which can take into account the strength degradation caused by cyclic loading. Second, we have attempted to evaluate the effects of cyclic characteristics of earthquake through seismic response analysis by using this model. As a result, the following two major characteristics are clarified.

1) When the duration time of the earthquake motion is long, the strength degradation becomes more predominant and the deformation of the structure becomes very large.
2) When the duration time is short, only a few pulse controls the earthquake response characteristics and the deformation of the structure does not progress.

As mentioned above, the post-peak behavior of RC structures depends on cyclic characteristics of the ground motion. Consequently, in order to verify the seismic performance of RC structures, it is important to conduct the dynamic response analysis by using our developed model considering the strength degradation.

REFERENCES


